OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

UNSATURATED SOIL MOISTURE DRYING AND WETTING DIFFUSION COEFFICIENT MEASUREMENTS IN THE LABORATORY

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16. ABSTRACT

Transient moisture flow in an unsaturated soil in response to suction changes is controlled by the unsaturated moisture diffusion coefficient. The moisture diffusion coefficient can be determined by measuring suction profiles over time. The laboratory testing approach involves measurement of the total suction changes with time using thermocouple psychrometers in cylindrical soil specimens with predetermined boundary conditions. The determination of the diffusion coefficient by this method is simple and relatively rapid and can be carried out on a routine basis in a geotechnical engineering laboratory. It is well-known that soils exhibit hysteresis with drying and wetting cycles. A similar hysteresis has been observed between the drying and wetting diffusion parameters for a number of undisturbed soil samples obtained from field borings across Oklahoma. The wetting diffusion coefficients are generally greater than the drying diffusion coefficients by a factor of up to 2.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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EXECUTIVE SUMMARY

Reliable estimates of soil water diffusivity are important in describing and predicting the movement of water in unsaturated soils. The diffusion of moisture through unsaturated soils is governed by the total suction gradients within the soil profile: with moisture traveling from regions of low total suctions (high water contents) to regions of high total suctions (low water contents). The unsaturated moisture diffusion coefficient controls transient moisture flow conditions within a soil mass in response to suctions or fluxes imposed at the boundaries of the soil mass.

The primary objectives of this project were (i) to develop an improved and unified testing protocol for measuring both the drying wetting diffusivity parameters on the same soil specimens; (ii) to improve the current testing equipment to perform both the drying test and wetting test; and (iii) to evaluate the hysteresis effect on the drying and wetting diffusion parameters. Based on the research conducted, the following findings are noted: (1) testing equipment was developed to obtain the drying and wetting diffusion coefficient measurements in the laboratory on the same soil specimens. The equipment can be used to run multiple tests at the same time under a controlled temperature environment with thermocouple psychrometers to obtain continuous total suction measurements with time. Laboratory tests were performed with soil samples taken from soil borings collected from different sites across Oklahoma. A wide range of diffusion coefficient measurements were obtained from a variety of soils from the sites. (2) for most soil specimens tested, the wetting diffusion coefficients are generally higher than the drying diffusion values by a factor of up to 2. (3) soils with significant numbers of cracks have much higher wetting diffusion parameter values than those with a few cracks. (4) the hysteresis effect between the drying and wetting parameters tends to be smaller for soils obtained from deeper depths from the ground surface than soils obtained from shallower depths.

The critical parameter that will control the rate at which moisture will move into an unsaturated soil is the soil moisture diffusivity coefficient. The determination of the unsaturated moisture diffusivity of a soil is important for the design of pavements, embankments, slopes, dams, and other geotechnical structures constructed in unsaturated soils. Once the moisture diffusion parameters have been established for the soils, the suction distribution in and around these structures can be predicted. The determination of the diffusion coefficients by this method is simple and relatively rapid and can be carried out on a routine basis in a geotechnical engineering laboratory.

CHAPTER I

INTRODUCTION

Knowledge of moisture diffusivity properties is required to predict water transport within unsaturated porous media. Obtaining realistic estimates of the moisture diffusion properties of unsaturated soils is essential to a number of pavement and geotechnical engineering applications such as design and analysis of subgrade soils, highway embankments and slopes, and prediction of shrinkage and swelling in soils supporting pavements and those behind retaining structures. The performance of civil structures constructed on unstable and expansive unsaturated soils is significantly affected by vertical deformations of the supporting local subgrade soils. Such deformations are controlled by suction variations in the soil mass. Compared to saturated soil conditions under the water table, water movement in the unsaturated zone above the water table (vadose zone) is far more complex due to the fact that the permeability versus suction and water content versus suction relationships are nonlinear in unsaturated soils.

The flow of moisture through unsaturated soils is governed by the total suction gradient within the soil profile; with moisture travelling from regions of low total suctions to regions of high total suctions (Mitchell, 1979). The unsaturated moisture diffusion coefficient controls transient moisture flow conditions within a soil mass in response to suctions or fluxes imposed at the boundaries of the mass. Current methods to determine the unsaturated moisture diffusion coefficient are expensive, difficult, and time consuming. Many of these approaches are based on the laboratory testing methodology provided by Bruce and Klute (1956). The Bruce-Klute method utilizes dry soils packed into a thin, horizontal soil column. The column is sufficiently long that it may be regarded of semi-infinite length. Water is introduced to one end of a horizontal soil column at a small but constant pressure for a measured time period. The moisture content at various locations along the soil column over time is then determined as the water front propagates through the soil. Finally, calculation of the moisture diffusivity is made using a procedure based on the Boltzmann transformation technique.

The relationship between water content and distance along the soil column is very essential in determining the diffusion properties of the soil. Determining the location of the water front in tests based on the Bruce-Klute method possess a serious problem for inhomogeneous soil columns. It often takes weeks or even months to measure the unsaturated diffusivity properties of fine grained soils such as clays (Fujimaki and Inoue, 2003). The method proposed by Bruce-Klute measures the wetting diffusion parameter. In addition, the hysteresis effect on the diffusivity parameter associated with the drying and wetting of soils due to seasonal variations has not been thoroughly investigated.

Mitchell (1979) proposed two simplified laboratory tests namely, the soaking test and evaporation test, to define water diffusion through an unsaturated soil using cylindrical Shelby soil columns of specified geometry. In these tests, the cylindrical surface and one end of the soil column are sealed while the other end is left open and exposed to the atmosphere or liquid of known suction. The distribution of suction at various locations over time is then determined as moisture propagates through the soil body. Finally, calculation of the wetting and drying diffusion coefficient is made using the diffusion equations proposed by Mitchell (1979).

The determination of the diffusion coefficient by Mitchell method is simple and relatively rapid compared to the Bruce-Klute method and other similar methods. This research adopts an improved method for laboratory measurements of the moisture diffusion coefficient that was originally developed by Mitchell (1979) with subsequent improvements described by Lytton et al. (2005). In a Texas Department of Transportation research project, Lytton et al. (2005) performed drying tests by exposing one end of a Shelby tube sample to the atmosphere while keeping the remaining surfaces sealed to induce moisture flow. Thermocouple psychrometers inserted into the specimen were used to measure changes in total suction over time as moisture evaporates from the exposed end. Thermocouple psychrometers permit measurement of changes in total suction over time as moisture evaporates from the exposed end. Fitting a theoretical solution to the data permits an estimate of the moisture diffusion coefficient.

The current testing protocol developed by Lytton et al. (2006) only dealt with the drying diffusion coefficient measurements. This report describes improvements in the current testing equipment and protocol for determination of wetting and drying diffusivity parameters in several areas. The new testing equipment developed at Oklahoma State University was used to perform wetting and drying tests on a number of soil samples. This research developed a unified testing protocol for measuring the diffusivity parameters.

It is well known that soils exhibit hysteresis with drying and wetting cycles. This research performed an evaluation of the hysteresis effect between the drying and wetting diffusion parameters for six different soils. The wetting diffusion coefficients were generally greater than the drying diffusion coefficients by up to a factor of two. The determination of diffusivity coefficients using Mitchell's approach provides a simple, economical and relatively rapid laboratory framework that can be used in DOT's and commercial laboratories on a routine basis.

CHAPTER II

THEORETICAL BACKGROUND

The performance of civil structures constructed on unsaturated, collapsible, and expansive soils is significantly affected by moisture movements in the supporting subgrade soils. This section describes the moisture diffusion equations outlined in the Bruce-Klute (water content approach) and the Mitchell (suction approach) methods.

2.1 Bruce-Klute Approach

Darcy's equation describing one-dimensional flow of water in unsaturated soils is:

$$Q = k(\theta)\frac{\partial \theta}{\partial \chi} \tag{1}$$

where Q is the soil water flux per unit area, θ is the volumetric water content, $k(\theta)$ is the unsaturated permeability, and x is the distance. Bruce and Klute (1956) derived a flow equation describing movement of water in a horizontal, semi-infinite unsaturated porous media from Equation 1 and the equation of continuity:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D(\theta)\frac{\partial \theta}{\partial x}\right) \tag{2}$$

where θ is the volumetric moisture content, t is the time since start of test, x is the horizontal distance from inlet, and D is the moisture diffusivity. Water is applied at one end of a horizontal long tube of air-dry or partially wet soil at a small but constant pressure and allowed to move into the soil column for a measured period of time. The column must be sufficiently long to be regarded as semi-infinite length. The Bruce-Klute boundary conditions for the test are:

$$\theta(x,t) = \theta_i \qquad \text{for } x > 0, \text{ and } t = 0 \tag{3}$$

$$\theta(x,t) = \theta_0 \qquad \text{for } x = 0, \text{ and } t > 0 \tag{4}$$

where θ_i is the initial moisture content of the system, and θ_0 is the inlet water content. Bruce and Klute (1956) showed that by incorporating the Boltzmann transformation, $\lambda = xt^{-0.5}$, Equation 2 is reduced to an ordinary differential equation

$$-\frac{\lambda}{2}\frac{d\theta}{d\lambda} = \frac{d}{d\lambda}\left(D(\theta)\frac{d\theta}{d\lambda}\right) \tag{5}$$

with boundary conditions

$$\theta = \theta_i \qquad \text{for } \lambda = \infty \ (\lambda \rightarrow 0) \tag{6}$$

$$\theta = \theta_0 \qquad \text{for } \lambda = 0 \tag{7}$$

Integration of Equation 5 from $\theta = \theta_i$ to $\theta = \theta_x$ yields:

$$D(\theta_x) = -\frac{1}{2}\left(\frac{d\lambda}{d\theta}\right)_{\theta_x} \int_{\theta_i}^{\theta_x} \lambda d\theta \tag{8}$$

or in terms of x and t and at constant t:

$$D(\theta_x) = -\frac{1}{2t}\left(\frac{dx}{d\theta}\right)_{\theta_x} \int_{\theta_i}^{\theta_x} x d\theta \tag{9}$$

where θ_x is θ at the distance x along the column. The only data requirements are water content measurements at one location or at many locations along the soil column over a measured time period to obtain a set of $\theta(x,t)$ data. Equation 9 can be evaluated using the following procedure Bruce and Klute (1956):

(a) Plot θ versus x curve from the experimental data, $\theta(x,t)$, i.e. θ as a function of x at a constant value of t.
(b) From the plot of θ versus x, evaluate the derivative by measuring the slope of the moisture content distribution curve and evaluate the integral by estimating the area under the curve using approximate methods at a series of values of θ_x.
(c) Calculate D at the values of θ_x used in step (b), thereby obtaining $D(\theta)$.

The conventional Bruce-Klute test method relies on evaluating slopes of the water content distribution curves and the area under the curves. However, experimental data obtained from this test exhibits natural scatter, thus making the evaluation of the slopes difficult. In addition, the inlet and wetting front slopes are difficult to measure accurately due to very small and large slopes respectively. To remedy this problem, many researchers have applied explicit functions to the experimental data obtained from the Bruce-Klute test with the intension of describing water diffusivity thereby avoiding measuring the slopes of the moisture distribution curves.

Cassel et al. (1968) based on the Bruce and Klute (1956) method presented a method of calculating soil-water diffusivity values using time dependent soil-water content distribution curves. This method involves experimentation over long time periods and diffusivity calculations are time consuming and can be troublesome especially for soils that shrink and swell. Clothier et al. (1983) decided to first fit a function to the measured data obtained from the Bruce-Klute test chosen from expressions derived in Philip (1960) to approximate the water content distribution curve. This made possible the derivation of a $D(\theta)$ function from this fitted expression circumventing the need to differentiate experimental data in which there is scatter. A drawback to this method is that the fitting function of Clothier et al. (1983) may not apply to all soils (Wang et al., 2004). Warrick (1994) developed an analytical expression for water diffusivity involving several hydraulic functions such as water content, hydraulic conductivity, and matric potential based on Philip (1969) procedure. However, measurement of the parameters requires laboratory procedures that are difficult, expensive, and time consuming (Tyner and Brown, 2004). Shao and Horton (1996) developed a method to estimate the water diffusivity of unsaturated soils using a nonhysteric analytical solution to horizontal redistribution based on general similarity theory. The method allows the water content of the inlet boundary to be variable with time and allows initial water content distribution to be variable with distance. Shao and Horton (1996) assumed a power function between the soil water diffusivity and the soil water content; however the form of their power function may not apply to all soils (Wang et al. 2004). Wang et al. (2004) developed a diffusivity expression based on hydraulic expressions provided by Brooks and Corey (1964) and Parlange (1971) while Tyner and Brown (2004) used D(θ) expression provided by van Genuchten (1980) to estimate diffusivity. The functions applied by Wang et al. (2004) and Tyner and Brown (2004) are based on soil hydraulic parameters.

Several approaches have been developed to estimate the water diffusivity in horizontal infiltration experiments; however, the intensive calculations, time-consuming measurement of soil parameters, and diffusivity functions not being applicable to all soils limit their application.

2.2 Mitchell Approach

Darcy's equation describing one-dimensional flow of water in unsaturated soils is:

$$Q = k(h)\frac{\partial h}{\partial x} \tag{10}$$

where Q is the soil water flux per unit area, h is the total head (total suction), k(h) is the unsaturated water coefficient of permeability, and x is the distance. Equation 10 is nonlinear due to the dependence of permeability on suction. In unsaturated soils, permeability is a function of total suction and is given by Laliberte and Corey (1967) as:

$$k(h) = k_0\left(\frac{h_0}{h}\right)^n \tag{11}$$

where k_0 is the saturated reference permeability, h_0 is the reference total suction, and n is the material constant. In Equation 11, total suction must be within the range for which Laliberte and Corey (1967) permeability relationship is valid.

Invoking the principle of conservation of mass with Equation 10 and Equation 11 leads to a nonlinear diffusion equation. For a special case n = 1, the solution reduces to a linear equation when suction is expressed on a logarithm scale, u = $\log|h|$. Mitchell (1979) used this case to describe one dimensional flow of moisture through an unsaturated porous media using a single moisture diffusivity coefficient α:

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{\alpha}\frac{\partial u}{\partial t} \tag{12}$$

where u is the total suction expressed on logarithm scale, x is the direction of moisture flow, α is the diffusion coefficient of the soil, and t is the elapsed time. Equation 12 defines the distribution of suction throughout the soil body as a function of space and time. Mitchell (1979) proposed two laboratory methods that could be performed to determine the diffusivity coefficient of unsaturated soils; namely wetting/soaking test and drying/evaporation test. In both tests the curved surface and one end of a cylindrical specimen are insulated and the other end is left open to permit flow of moisture into or out of the sample. The diffusion coefficient of the soil can be measured by determining the rate of change of suction with time in the soil specimen.

2.2.1 Drying Test

The solution to the drying problem considers initial and boundary conditions:

$$\text{Inital Suction:} \qquad u(x,0) = u_0 \tag{13}$$

$$\text{Sealed Boundary:} \qquad \frac{\partial u(0,t)}{\partial x} = 0 \tag{14}$$

$$\text{Open Boundary:} \qquad \frac{\partial u(l,t)}{\partial x} = -h_e[u(l,t) - u_a] \tag{15}$$

Mitchell (1979) solved Equation 12 using the separation of variables, Fourier series, and properties of orthogonal functions for known initial and boundary conditions (Equations 13, 14, and 15) to determine the unsaturated diffusion coefficient for the drying test as:

$$u(x,t) = u_a + \sum_{n=1}^{\infty} \frac{2(u_0 - u_a)\sin z_n}{z_n + \sin z_n \cos z_n} e^{\left(\frac{-z_n{}^2 \alpha t}{L^2}\right)} \cos\left(\frac{z_n x}{L}\right) \tag{16}$$

where u(x,t) is suction as a function of location and time, u_a is the atmospheric suction, u_0 is the initial suction in soil, t is the elapsed time since start of test, L is the length of sample, x is the psychrometer distance from closed end, α is the diffusion coefficient, z_n is obtained from the solution of $\cot z_n = z_n/h_eL$, and h_e is the evaporation coefficient, which is equal to 0.54 cm^{-1} based on Mitchell (1979) recommendation. A soil specimen originally at a known suction, is sealed at one end and the curved surface and allowed to lose moisture to atmosphere of known suction from one open end.

2.2.2 Wetting Test

The solution to the wetting problem considers initial and boundary conditions:

$$\text{Inital Suction:} \qquad u(x,0) = u_0 \tag{17}$$

$$\text{Sealed Boundary:} \qquad \frac{\partial u(0,t)}{\partial x} = 0 \tag{18}$$

$$\text{Open Boundary:} \qquad u(l,t) = u_l \tag{19}$$

Mitchell (1979) solved Equation 12 using Laplace transforms for known initial and boundary conditions (Equation 17, 18, and 19) to determine the unsaturated diffusion coefficient for the wetting test as:

$$u(x,t) = u_s + \frac{4(u_s - u_0)}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{2n-1} e^{\left(\frac{-(2n-1)^2 \pi^2 \alpha t}{4L^2}\right)} \cos\left(\frac{(2n-1)\pi t}{2L}\right) \tag{20}$$

where u_s is the soaking suction. A soil specimen originally at a known suction, is sealed at one end and the curved surface and exposed to a liquid of known suction at the open end. The solutions to Equation 16 and Equation 20 require an initial estimate of the diffusion coefficient; and with suction measurements at discrete locations over time, the diffusion coefficients of the soil can be easily estimated with the use of an Excel Worksheet.

2.3 Hysteresis in Unsaturated Soils

The drying and wetting process of a near surface unsaturated soil mass will yield hysteric moisture flow patterns. This variation in soil behavior is primarily attributed to the following (Tindall and Kunkel, 1999):

- *Geometric or "Ink Bottle" Effect*: Variations in the geometric sizes and shapes of soil pores will cause geometric hysteresis. Soil pores are generally irregular and are connected by narrow passageways of various sizes.
- *Contact Angle Effect*: The contact angle and radius of curvature of the soil-water on the pore wall are greater for a receding meniscus than an advancing meniscus. This results in a tendency for drying process to exhibit higher suction values than wetting process for given water content. However contact angle hysteresis can also be attributed to impurities in the soil, particle and pore size, surface roughness, and other factors.
- *Entrapped Air*: In wetting process, the water displaces soil-air from the atmosphere. However, considerable amount of entrapped air will remain in the system because of dead-end or occluded pores. The presence of entrapped air further reduces the water content of a newly wetted soil and accentuates the hysteresis effect.
- *Shrinkage and Swelling*: Cycles of drying and wetting cause shrinkage and swelling or aging phenomena. This causes differential changes in soil structure depending on drying and wetting history of the soil (Hillel and Mottes, 1966). Subsequent absorption and desorption of air during the drying and wetting process causes changes in size and distribution of pores resulting in variations in water content, hence hysteresis.

The difference between the drying and wetting curves maybe as much as one to two orders of magnitude (Fredlund, 2002). The hysteresis effect is in general more pronounced in coarse-textured soils in the low- suction range, where pores may empty at an appreciably larger-suction than that at which they fill (Ng and Menzies, 2007)

In the field, numerous cycles of partial dying and wetting occur due to seasonal variations. Fluctuations in moisture movement affect the performance of civil structures built on unsaturated soils. A critical step in design and analysis of civil structures lies in the ability to characterize moisture flowing through an unsaturated soil. Mitchell (1979) uses soil total suction instead of volumetric water content that is used in the Bruce and Klute (1956) approach. A major difficulty with the use of the moisture content approach is that the moisture content profile for unsaturated soils is difficult to predict because it can show wide variations and discontinuities (Fredlund and Rahardjo, 1993). Soil suction profiles tend to be uniform and are easier to predict as they approach towards equilibrium under certain suction or flux boundary conditions (Mitchell, 1979).

The Bruce-Klute method only estimates the wetting diffusivity parameter. The Mitchell method can be used to determine both the drying and wetting diffusion coefficient. Thus hysteresis effect between the drying and wetting parameters can be investigated using Mitchell's laboratory tests. In addition, the Mitchell method can use both disturbed and undisturbed soil specimens while the Bruce-Klute method only uses repacked therefore undisturbed samples. When using disturbed samples, it is difficult to preserve in-situ soil pore size and distribution and soil structure to mimic field conditions. Realistic estimates to diffusivity of unsaturated soil in the field can be obtained using undisturbed samples.

Dynamics of moisture movement is extremely complex in unsaturated soils, especially if there are cracks and different permeable soil components in the whole soil mass. Moisture movement from the soil matrix through the cracks and different permeable soil layers can be very different and complex and this process can be extremely difficult to model. However, if total suction as a function of space coordinates and time is defined, then the moisture flow at any location can be specified by the diffusion equation.

CHAPTER III

LABORATORY TEST METHODS

The drying and wetting unsaturated soil diffusion coefficients can be determined by measuring total suction over time in cylindrical soil specimens in the laboratory. Moisture flow is induced in the cylindrical specimens by sealing all the boundaries except one end which is exposed to the atmosphere of known very high suction or liquid of known very low suction.

Thermocouple psychrometers (Figure 1) are imbedded in soil specimens at various locations to monitor changes in total suction over time as moisture evaporates from or a liquid enters into the soil specimen using the exposed end. The filter paper method was used to determine the initial total suction of the soil specimens prior to testing. The relative humidity in the testing room was measured and used to determine the atmospheric suction during the testing period. After obtaining the suction and corresponding time measurements, the diffusivity coefficient is determined using Equation 16 and Equation 20. Once the soil diffusion coefficients have been determined, prediction of the suction distribution in an unsaturated soil mass is possible through the solution of the diffusion equations. Also, the hysteresis effect on the drying and soaking diffusivity coefficients can be investigated.

Before using the psychrometers, they are calibrated using salt solutions with known water potential. The relationship between thermocouple microvolt outputs versus water potential values of the salt solution provide a calibration relationship for each psychrometer.

3.1 Calibration of Psychrometers

The calibration is performed using salt solutions of different molarities for a suitable range of psychrometer suction measurements, typically 2 to 4 log kPa osmotic suction (Table 1).

The following apparatus is required:

- Stainless steel wire-shield thermocouple psychrometers from Wescor Inc.
- Sodium Chloride (NaCl) salt.
- Balance with at least 0.0001 g accuracy.
- Distilled/deionized water to make salt solutions.
- Measuring cylinder to determine amount of distilled water required.
- Plastic bottles to store the salt solutions.
- Glass jars to calibrate a number of psychrometers at one time.
- Measuring plastic bowls, spatula, rubber stoppers with lengthwise hole, silicon sealant, and electrical tape.
- CR 7 Datalogger from Campbell Scientific Inc.
- Water bath with cylindrical tubes to hold specimen and temperature control unit.
- Temperature controlled room.

The salt solutions are prepared as follows:

1. Use Table 1 to determine the amount of NaCl salt to be used depending upon the suction value and quantity of solution (in liter) required.
2. Weigh the salt on the balance. Seal the bottle containing the salt shortly after use to prevent the salt from forming clumps if exposed to the atmosphere.
3. Pour the salt and required amount of distilled/deionized water in a plastic bottle.
4. Seal the plastic bottle with electrical tape and shake vigorously to dissolve the salt.
5. Repeat steps 1 to 4 for all salt concentrations.

The psychrometers are calibrated as follows:

1. Make holes, depending on the size of the rubber stoppers, in the lid of a glass jars to be used in calibration process.
2. Place each psychrometer wire in the lengthwise hole of a rubber stopper and tightly fit them into holes made in the lid while providing sufficient length of wire that will enable all the psychrometer tips to be wholly suspended in the salt solution in the glass jar during calibration.
3. Put silicon sealant on the contact areas between the psychrometers and stoppers as well as contact area between the rubber stoppers and lids to prevent loss or gain of moisture during calibration. Allow sealant to dry for half an hour.
4. Pour prepared salt solution into glass jar enough to immerse the psychrometer tips into the solution. Place the lid with psychrometers onto the glass jar and seal it with electrical tape to prevent loss or gain of moisture (see Figure 2).
5. Place the glass jar in one of the water bath cylindrical tubes (Figure 3) and maintain the water bath at constant temperature of 25±0.1 ^{o}C using temperature control unit. Leave the setup for an hour for thermal and vapor equilibrium of the psychrometers.
6. Connect psychrometers to the CR 7 Datalogger (Figure 4) to collect total suction readings obtained by the psychrometers for at least an hour.
7. After calibration, clean the psychrometers by vigorously rinsing them in distilled/deionized water and allow them to air dry for at least one hour.
8. Repeat steps 4 to 7 for salt solutions with different suction values for all the psychrometers.
9. For each psychrometer, plot the equilibrium microvolt values obtained from the psychrometers against their corresponding suction values for all the different salt solutions.

A typical calibration curve obtained from this process is shown in Figure 5.

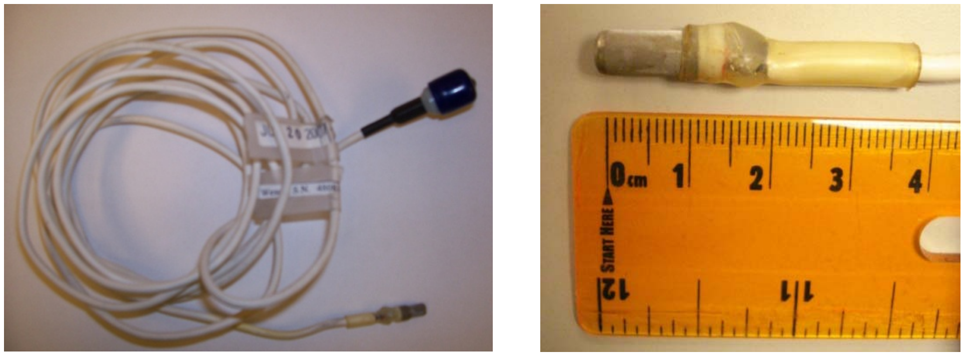

Figure 1: Stainless Steel Wire-Shield Thermocouple Psychrometer

Table 1: NaCl Osmotic Suctions for Psychrometer Calibration (Bulut et al., 2001)

Molality of NaCl (m)	Osmotic Suction (bar)	Osmotic Suction (kPa)	Osmotic Suction (log kPa)	Osmotic Suction (pF)	Amount of NaCl (g/liter)
0.10	0.4799	47.9937	1.6812	2.6897	5.8442
0.02	0.9502	95.0235	1.9778	2.9863	1.1688
0.05	2.3390	233.9024	2.3690	3.3775	2.9221
0.10	4.6232	462.3164	2.6649	3.6735	5.8442
0.20	9.1608	916.0757	2.9619	3.9704	11.6885
0.30	13.7019	1370.1870	3.1368	4.1453	17.5327
0.40	18.2658	1826.5788	3.2616	4.2702	23.3770
5.00	22.8615	2286.1486	3.3591	4.3676	292.2123
0.60	27.4942	2749.4170	3.4392	4.4478	35.0655
0.70	32.1682	3216.8152	3.5074	4.5159	40.9097
0.80	36.8870	3688.6952	3.5669	4.5754	46.7540
0.90	41.6531	4165.3100	3.6196	4.6282	52.5982
1.00	46.4691	4646.9124	3.6672	4.6757	58.4425
1.20	56.2615	5626.1507	3.7502	4.7587	70.1310
1.40	66.2798	6627.9768	3.8214	4.8299	81.8195
1.50	71.3777	7137.7693	3.8536	4.8621	87.6637
1.60	76.5384	7653.8384	3.8839	4.8924	93.5079
1.80	87.0498	8704.9848	3.9398	4.9483	105.1964
2.00	97.8247	9782.4672	3.9904	4.9990	116.8849
2.20	108.8735	10887.3465	4.0369	5.0454	128.5734
2.40	120.2025	12020.2474	4.0799	5.0884	140.2619
2.50	125.9757	12597.5653	4.1003	5.1088	146.1062

1 mole of NaCl = 58.442468 grams

Figure 2: Calibration Setup of Thermocouple Psychrometers

Figure 3: Water Bath for Drying and Wetting Test

Figure 4: CR 7 Datalogger from Campbell Scientific Inc.

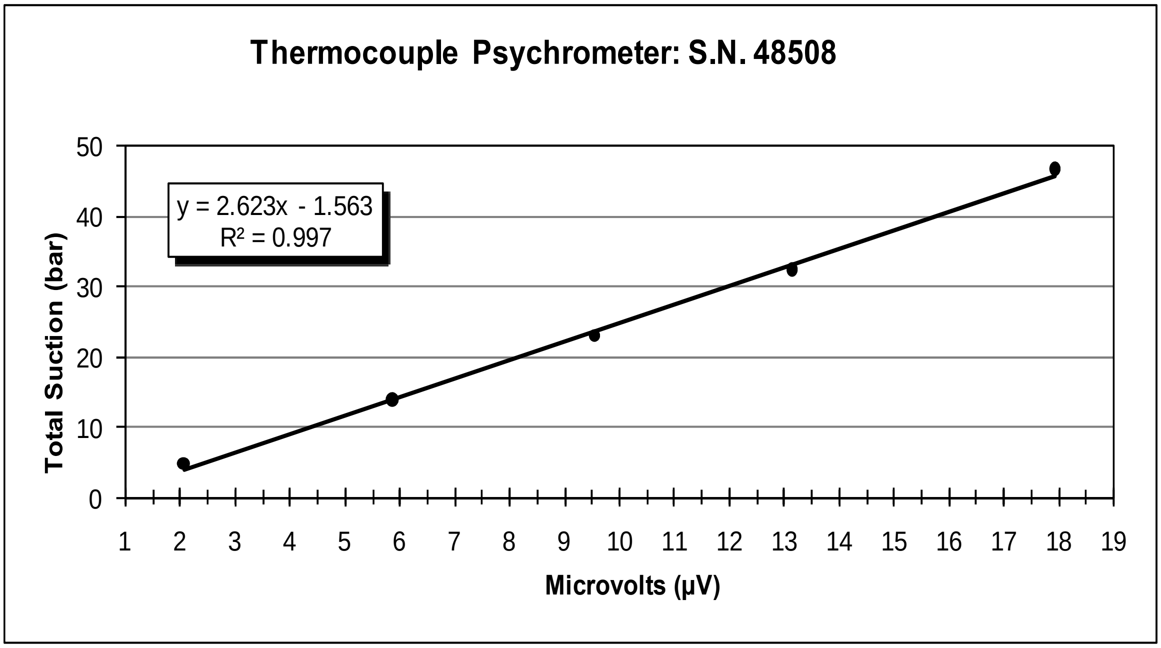

Figure 5: Typical Thermocouple Psychrometer Calibration Curve

3.2 Measurement of Soil Diffusion Coefficients

The process for determining the drying and wetting soil diffusion coefficients is based on the laboratory test procedures proposed by Mitchell (1979) and modified by Lytton et al. (2005). The unsaturated soil diffusivity coefficients are measured using thermocouple psychrometers embedded in the soil specimen while allowing moisture loss to the atmosphere of known suction (drying/evaporating test) or exposing the specimen to a liquid of known suction (wetting/soaking test) from only one open end of the soil specimen. Psychrometers measure total suction profile in the soil specimen over time.

The following apparatus are required to perform total suction measurements using thermocouple psychrometers:

- Stainless steel wire-shield thermocouple psychrometers from Wescor Inc.
- Drill-bit to drill holes into the soil specimen.
- Measuring ruler, plastic wrap, aluminum foil, and scissors.
- CR 7 Datalogger from Campbell Scientific Inc.
- Water bath with cylindrical tubes to hold specimen and temperature control unit.
- Temperature controlled room.
- Dehumidifier to control the relative humidity.

Total suction measurement using thermocouple psychrometers is performed as follows:

3.2.1 Drying Diffusion Coefficient Measurements

1. Select a soil specimen of about 20 cm long and trim the ends to provide a planar surface. Record the length (L) of the specimen.
2. Choose which end of the specimen will be exposed to the atmosphere of very high suction and mark psychrometer positions on the lateral side of the specimen. Mark the first psychrometer position about 5 cm from the exposed end. Provide a 3 to 5 cm interval between psychrometers. The distance from the open end to the first psychrometer may be changed depending on the soil type, soil moisture condition, and/or method of making psychrometer holes in the specimens.
3. Use a drill-bit to make holes for psychrometers keeping the depth of the hole approximately half the diameter of soil specimen. The diameter of the holes should be large enough for psychrometers to fit precisely.
4. Insert calibrated psychrometers into the holes and tightly seal the holes on the surface of the specimen with small pieces of soil cuttings obtained from the specimen in step 1 to prevent loss or gain of moisture. Record the psychrometer numbers and their distances from the closed end.
5. Seal the whole specimen; except the one end that will be exposed to the atmosphere, with plastic wrap and aluminum foil to prevent loss or gain of moisture (Figure 6).
6. Place the specimen in one of the water bath tubes (Figure 3) exposing the open end to the atmosphere. Maintain the water bath at 25±0.1 ^{o}C throughout the testing period. Perform the drying test in a temperature and humidity controlled room. Maintain the testing room at 25±0.1 ^{o}C and use the dehumidifier to control the relative humidity in the room.
7. Connect psychrometers to the datalogger to collect total suction values obtained by the psychrometers.
8. Repeat steps 1 to 7 for each soil specimen.

3.2.2 Wetting Diffusion Coefficient Measurements

1. Select a soil specimen of about 20 cm long and trim the ends to provide a planar surface. Record the length (L) of the specimen.
2. Choose which end of the specimen will be exposed to a liquid of very low suction (distilled/deionized water) and mark psychrometer positions on the lateral side of the specimen. Mark the first psychrometer position about 5 cm from the exposed end. Provide a 3 to 5 cm interval between psychrometers. The distance from the open end to the first psychrometer may be changed depending on the soil type, soil moisture condition, and/or method of making psychrometer holes in the specimens.
3. Use a drill-bit to make holes for psychrometers keeping the depth of the hole approximately half the diameter of soil specimen. The diameter of the holes should be large enough for psychrometers to fit precisely.

4. Insert calibrated psychrometers into the holes and tightly seal the holes on the surface of the specimen with small pieces of soil cuttings obtained from the specimen in step 1 to prevent loss or gain of moisture. Record the psychrometer numbers and their distances from the closed end.
5. Seal the whole specimen; except the one end that will be exposed to the atmosphere, with plastic wrap and aluminum foil to prevent loss or gain of moisture (Figure 7).
6. Place the specimen in one of the water bath tubes with piezometer (Figure 3) exposing the open end to distilled/deionized water. Maintain the water bath at 25±0.1 ^{o}C throughout the testing period. Perform the drying test in a temperature and humidity controlled room. Maintain the testing room at 25±0.1 ^{o}C and use the dehumidifier to control the relative humidity in the room.
7. Connect psychrometers to the datalogger to collect total suction values obtained by the psychrometers.
8. Repeat steps 1 to 7 for each soil specimen.

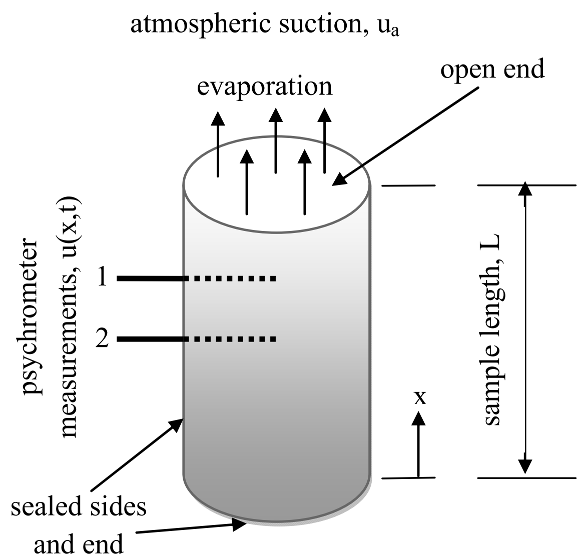

Figure 6: Drying Test Cylindrical Soil Specimen

The duration of the test is typically 4 to 7 days for either the drying test or soaking test. The drying test and wetting test can be performed on the same soil specimen one process followed by another. Controlling the temperature and relatively humidity of the testing environment allows reliable estimates of the diffusion coefficient to be obtained. The determination of the diffusion coefficient by this method provides a simple, economical, and relatively rapid method of determining the diffusivity properties of an unsaturated soil.

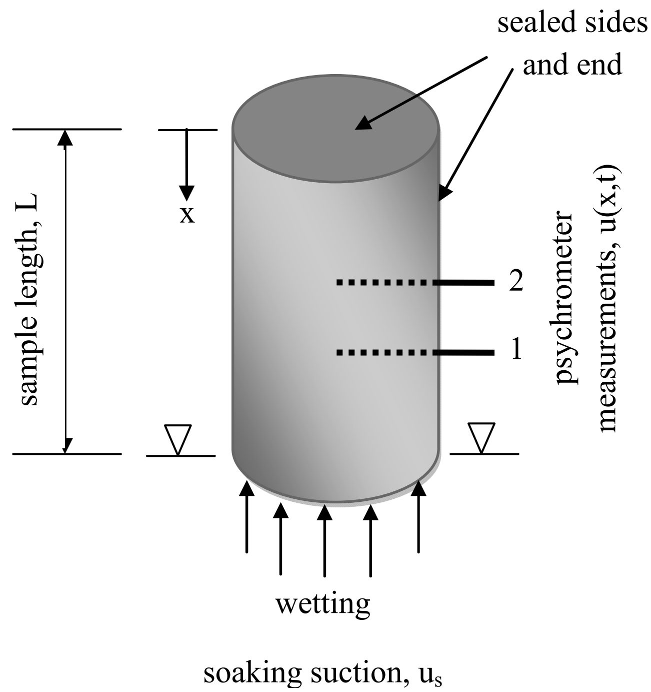

Figure 7: Wetting Test Cylindrical Soil Specimen

3.3 Measurement of Initial Suction

Initial suction in the soil prior to testing is determined using the filter paper method. The testing procedure proposed by Lytton et al. (2006) was adopted for the total suction measurements. Schleicher & Schuell No. 589 – White Hard (WH) filter papers were used in this study. Filter papers work on the premise that vapor equilibrium will occur between the soil and the paper in a temperature controlled environment; thus the total suction in the soil will be the same as that of the filter paper.

Prior to testing, filter papers are calibrated to determine the relationship between the equilibrium water content and relative humidity using a range of salts solutions with known water potentials. The calibration curve developed by Bulut et al. (2001) for this brand of filter paper was adopted in this study (Figure 8).

The following apparatus are required to perform a total suction test using filter paper:

- Schleicher & Schuell No. 589 – White Hard (WH) filter papers
- Glass jars to perform total suction filter paper test.
- Oven at 110±5 ^{o}C to dry the filter paper.
- Balance with at least 0.0001 g accuracy.
- Aluminum moisture tins, ring supports, tweezers, latex gloves, electrical tape, aluminum block, ice chest, knife, and spatula.
- Constant temperature room.

Procedure for determining the initial suction using filter papers is as follows:

1. Cut a portion of Shelby tube soil specimen to fill about 2/3 of the glass jar (see Figure 9).
2. Insert the sample in a glass jar and place some soil cuttings from step 1 in the sides of the jar to ensure that the sample does not move in the glass jar.
3. Place a clean ring-type support on top of the soil specimen to provide a non-contact surface between the filter paper and the soil. The diameter of the ring is smaller than that of the filter paper while its height leaves sufficient room for filter papers. Ensure that filter papers do not make contact with the glass lid or soil specimen.
4. Place two filter papers, one on top of the other on the ring-type support using tweezers. Make sure the filter papers do not make contact with soil or the glass jar (Figure 9).
5. Place the lid and seal tightly with electrical tape. This helps prevent any loss or gain of moisture that might occur.
6. Carry the glass jar to the ice chest which is in a temperature controlled room for equilibration to occur.
7. Repeat steps 1 to 6 for each soil specimen.

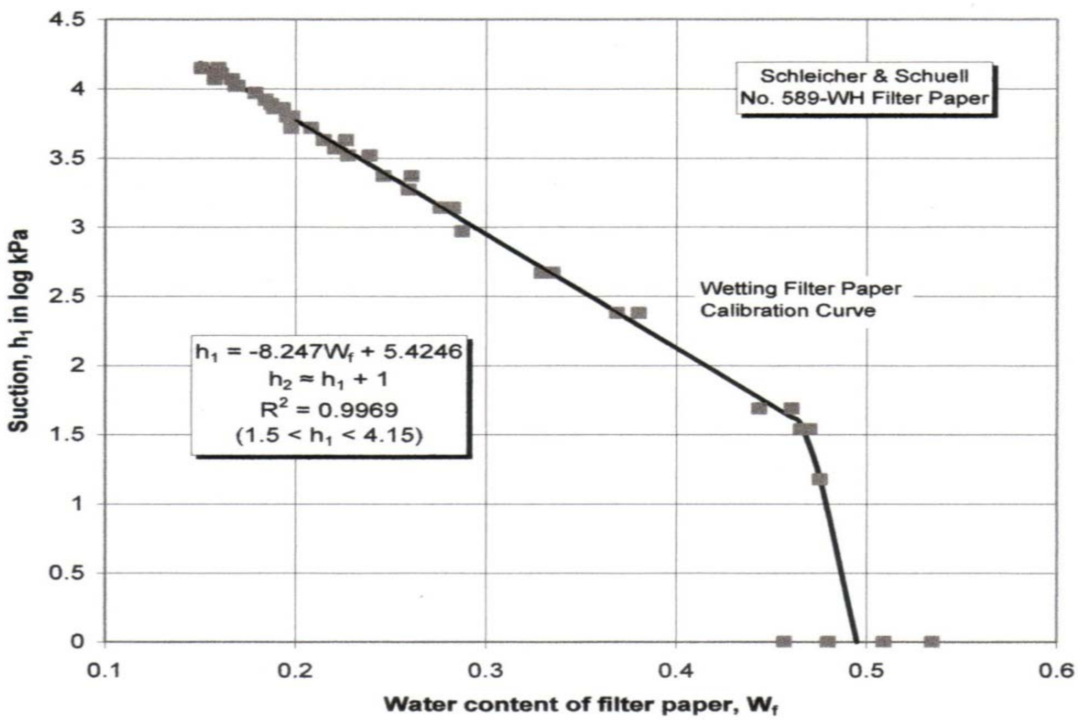

Figure 8: Filter Paper Calibration Curve (Bulut et. al, 2001)

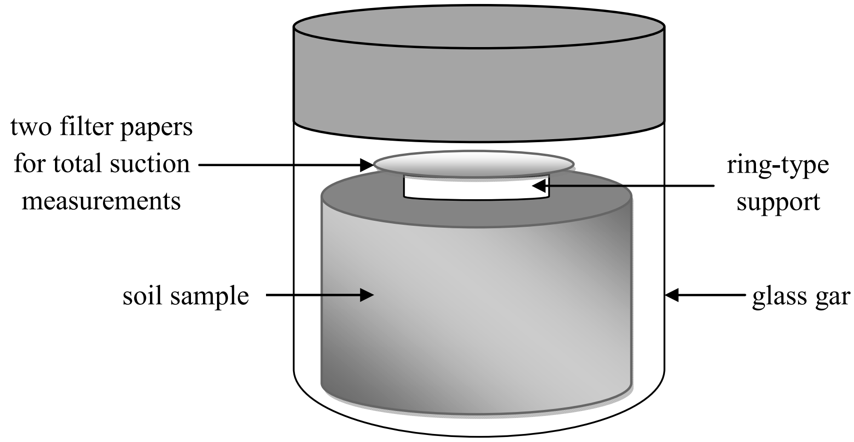

Figure 9: Total Suction Measurements using Filter Papers

Equilibration process takes about one week. At equilibrium, the suction of the soil and filter papers will be the same. After equilibration, the wet filter papers are measured to determine their water content as follows:

8. Wear latex gloves before touching any filter paper apparatus.
9. From a temperature controlled room, determine the number of cans to be used for water content measurements. For each tin, record (in Table 2) the cold tare mass (Tc) and corresponding moisture tin number.
10. Pick one glass jar from the ice chest in the temperature controlled room.
11. Open the glass jar and use tweezers to place the filter papers into separate moisture tins and close the lids. This process should take a few seconds.
12. Immediately place each can onto the balance and quickly record (in Table 2) the mass of cold tare can plus wet filter paper (M1). Record whether it is a top or bottom filter paper.
13. Make a record of all the information pertaining to the soil specimen such as boring number, sample number, sample depth in the worksheet.
14. Repeat steps 10 to 13 for every glass jar.
15. Place all the tare cans inside the oven with their lids half open to allow evaporation. Keep oven temperature at 110±5 ^{o}C and allow filter papers to dry for at least 10 hours.

Measurements of the dry filter papers are performed as follows:

16. Wear latex gloves before touching any filter paper apparatus.
17. Close the cans with their lids while still in the oven and allow equilibration to occur for about 5 minutes.
18. Pick one can from the oven and place it on an aluminum block for about 20 seconds to cool down.
19. Immediately place the can on the balance and record the mass of hot tare plus dry filter paper (M2) in Table 2.

20. Take the filter paper out of the tare can and immediately record the hot tare can mass (Th) in Table 2.
21. Repeat steps 18 to 20 for all the hot tare cans in the oven.

Complete Table 2 by determining the water content of each filter paper using the following calculations:

Mass of dry filter paper, Mf = M2 – Th
Mass of water in filter paper, Mw = M1 – M2 – Tc + Th
Water content of filter Paper, W_f = Mw / Mf

Soil suction calculations are performed on every filter paper to obtain the initial total suction using the wetting filter paper calibration curve (Figure 8) proposed by Bulut et al. (2001) as follows:

Total Suction (log kPa), $h_1 = -8.247W_f + 5.4246$ ($h_1 > 1.5$ log kPa)
Total Suction (pF), $h_2 = -8.247W_f + 6.4246$ ($h_2 > 2.5$ pF)

Report the total suction values to the nearest two decimal places in log kPa or pF.

3.4 Measurement of Atmospheric Suction

A digital thermo-hygrometer was used to determine the relative humidity in the laboratory. The relative humidity is measured several times in the day and an average of the values is obtained for the duration of the diffusion test for every soil specimen. The atmospheric suction was then calculated using Kelvin's equation (Fredlund and Rahardjo, 1993) given by:

$$h = \left(\frac{RT}{V}\right) ln(RH) \tag{21}$$

where h is the total suction, R is the universal gas constant, T is the absolute temperature, V is the molecular volume of water, and RH is the relative humidity.

3.5 Interpretation of Soil Diffusion Test Data

Using the total suction and corresponding time data from the drying and wetting process, the unsaturated drying and wetting diffusion coefficients can be determined. The suction versus time data is then fit with a theoretical line (Figure 10) depicting suction profile for the soil specimen.

Data interpretation protocol proposed by Aubeny et al. (2003) was employed to determine the drying and wetting moisture diffusivity coefficients. The procedure can be summaried as follows:

1. Make an initial estimate of α to compute a theoretical suction value corresponding to each measurement location (x) and measurement time (t) using Equation 5 for drying test or Equation 6 for the wetting test.

2. Compute the error (E) between the theoretical suction values (u_{theo}) and measured suction values (u_{meas}) for drying test or wetting test; so $E = u_{theo} - u_{meas}$.
3. Calculate the sum of squared errors (E_{sum}) for all suction measurements for drying test or wetting test; so $E_{sum} = \Sigma (u_{theo} - u_{meas})^2$.
4. Optimize α (from step1) to minimize E_{sum} for all suction measurements using a trial and error approach for drying test or wetting test.

Report the soil diffusivity coefficient values to the nearest 4 decimal places in cm^2/min. Hand calculations of Equations 5 and Equation 6 is not practical. These equations can simply be programmed using any programming languages, or instead an Excel Worksheet can be used. Microsoft Excel program was used to plot the measured and theoretical suction data (Figure 10).

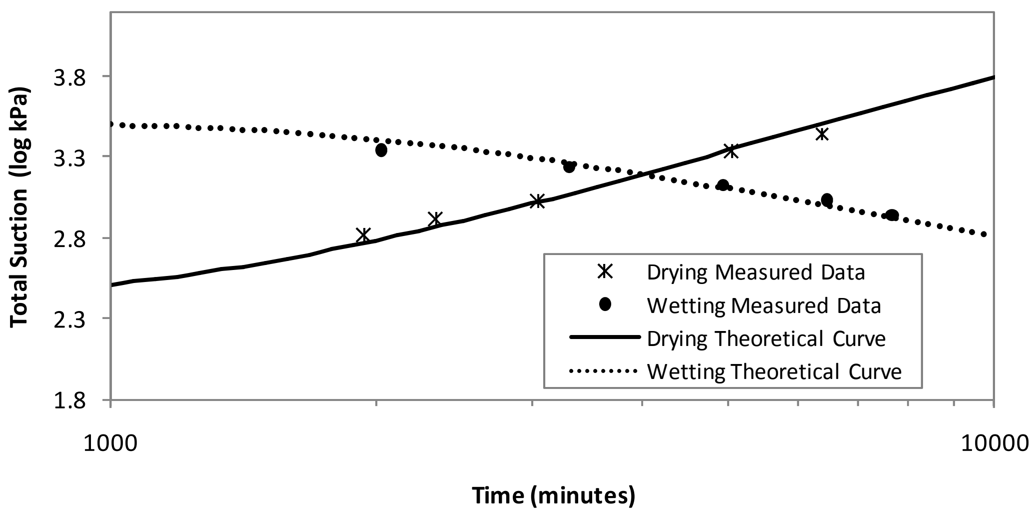

Figure 10: Theoretical Verses Measured Total Suction Values with Time

Table 2: Worksheet for Filter Paper Suction Measurements

FILTER PAPER METHOD SUCTION MASUREMENTS WORKSHEET										
Tested by:										
Date Tested:										
Date Sampled:										
Borimg No.										
Sample No.										
Depth										
Moisture Tin No.										
Total or Matric Suction (circle)		Total Matric	Total Matric	Total Matric	Total Matric	Total Matric	Total Matric	Total Matric	Total Matric	Total Matric
Top or Bottom Filter Paper (circle)		Top Bott	Top Bott	Top Bott	Top Bott	Top Bott	Top Bott	Top Bott	Top Bott	Top Bott
Cold Tare Mass, g	Tc									
Mass of Wet Filter Paper + Cold Tare Mass, g	M1									
Mass of Dry Filter Paper + Hot Tare Mass, g	M2									
Hot Tare Mass, g	Th									
Mass of Dry Filter Paper, g (M2-Th)	Mf									
Mass of Water in Filter Paper, (M1-M2-Tc+Th)	Mw									
Water Content of Filter Paper, (Mw / Mf)	W_f									
Suction, log kPa (Bulut et al., 2001)	h_1									
Suction, pF (Bulut et al., 2001)	h_2									
Average Suction										

CHAPTER IV

RESULTS AND DISCUSSIONS

Six different soils, namely SOIL A, B, C, D, E, and F, from Oklahoma Department of Transportation (ODOT) were tested to determine the wetting and drying diffusivity parameters. The results are summarized in Table 3 and the curve fits to the measured data are shown in Appendix A. These soils consisted of 7.28 cm diameter undisturbed Shelby tube samples obtained at depths of 0.00 to 82.30 cm. Sample lengths varied from 11.2-19.5 cm depending on the length of soil columns provided. Before testing, the soil samples had initial suctions ranging from 1.12-3.35 log kPa. The atmospheric suction in the testing room was relatively constant ranging from 5.20-5.36 log kPa.

In this research the wetting (α_{wet}) and drying (α_{dry}) diffusion coefficients were determined on the same soil specimen for every sample. For most samples, the testing scheme adopted involved performing the drying process first followed by the wetting process in order to obtain suitable range of suction measurements that covered the entire psychrometer range of about 2.5-3.8 log kPa for either the evaporating or soaking test. Two psychrometers were used in each test.

The estimated diffusivity coefficients (Table 3) indicate the following:

Soil A

- α_{wet} values are generally higher than α_{dry} values by a magnitude of 1.1-3.5. This may be attributed to cracks and root holes in the specimen which makes it possible the increased rate at which water will enter a soil.
- The samples obtained from depths approximately above 44.20 cm have bigger differences between α_{wet} and α_{dry} than those obtained below 44.20 cm. Samples from shallower depths tend to have more natural cracks and vegetative influence. These samples tend to have a larger α_{wet} value resulting in more hysteresis between the parameters.
- Samples from depth above 44.20 cm generally have higher α values compared to those from depth below 44.20 cm.
- Where the wetting test was done before the drying test, the difference between the coefficients is bigger than that of the other specimens. This may be a result of not being able to obtain the entire psychrometer suction range during the soaking test for determining α_{wet} values resulting in much bigger α_{wet} values.
- Sample A8 had a crack developed near the psychrometer probably as a result of drilling resulting in an α_{wet} values much higher than the other values in this group. This suggests a significant crack in a soil mass may significantly affect the rate at which water moves into a soil during the wetting process.
- Generally, for the soil in this group, α_{dry} values were between 1.47-10.53 cm^2/min and α_{wet} values were between 2.70-12.72 cm^2/min.

Soil B

- α_{wet} values are generally higher than α_{dry} values by a magnitude of 1.4-3.9. This may be attributed to cracks and root holes in the specimen which makes it possible the increased rate at which water will enter a soil.
- The differences between α_{wet} and α_{dry} values for samples obtained above approximately 39.62 cm depth appear to be smaller than for those samples obtained below 39.62 cm. This behavior is the opposite of what was observed in Soil A.
- Samples obtained above 39.62 cm depth appear to have larger α_{dry} values and smaller α_{wet} values compared to those obtained below 39.62 cm.
- B2 and B4 had several cracks along soil column before testing. These cracks may have contributed to the somewhat higher α_{wet} value compared to the other specimens.
- Generally, for the soils in this group, α_{dry} values were between 1.34-5.83 cm^2/min and α_{wet} values were between 3.74-6.87 cm^2/min.

Soil C

- α_{wet} values are generally higher than α_{dry} values by a magnitude of 1.2-1.6. This may be attributed to cracks and root holes in the specimen which makes possible the increased rate at which water will enter a soil.
- The α_{dry} and α_{wet} values are generally much bigger than those of the other soil samples. This soil was much softer, silty organic soil. It took the least time to run tests on Soil C.
- Generally, for the soils in this group, α_{dry} values were between 5.53-13.21 cm^2/min and α_{wet} values were between 7.63-15.26 cm^2/min.

Soil D

- α_{wet} values are generally higher than α_{dry} values by a magnitude of 0.8-2.3. This may be attributed to cracks and root holes in the specimen which makes it possible the increased rate at which water will enter a soil.
- The α_{dry} and α_{wet} values are generally much smaller than those of the other soil samples. This soil was generally wet, stiff clay. It took the most time to run tests on Soil D.
- The differences between α_{wet} and α_{dry} values are significantly smaller for Soil D than the other soil specimens. Soil D is much stiffer clay compared to the other five soils tested.
- Generally, for the soils in this group, α_{dry} values were between 0.63-1.28 cm^2/min and α_{wet} values were between 0.95-1.93 cm^2/min.

Soil E

All the specimens tested were obtained from depths near the ground surface.

- α_{wet} values are generally higher than α_{dry} values by a magnitude of 0.7-2.3. This may be attributed to cracks and root holes in the specimen which makes it possible the increased rate at which water will enter a soil.
- Generally, for the soils in this group, α_{dry} values were between 1.18-4.16 cm^2/min and α_{wet} values were between 1.63-5.89 cm^2/min.

Soil F

All the specimens tested were obtained from depths near the ground surface.

- α_{wet} values are generally higher than α_{dry} values by a magnitude of 0.6-1.5. This may be attributed to cracks and root holes in the specimen which makes it possible the increased rate at which water will enter a soil.
- Generally, for the soils in this group, α_{dry} values were between 1.21-3.47 cm^2/min and α_{wet} values were between 1.63-3.37 cm^2/min.

The determination of the drying and wetting diffusion parameters permits an estimate of the rate at which water will move into and out of the soil both vertically and horizontally, and can also be used to estimate the depth of the moisture active zone within the unsaturated soil profile. Unlike the Bruce and Klute method which estimates only the wetting diffusion parameter, the Mitchell method can estimate both the drying and wetting diffusion coefficients.

Table 3: Summary of Diffusion Coefficient Test Results

Sample No.	Depth (cm)	Testing Sequence	Drying Diffusion Coefficient $\alpha_{dry} \times 10^{-3}$ (cm^2/min)	Wetting Diffusion Coefficient $\alpha_{wet} \times 10^{-3}$ (cm^2/min)	Remarks
SOIL A					
A1	9.14-38.40	First performed drying test then wetting test	8.1579	12.7158	With small amount of gravel and silt, shrinkage cracks
A2	38.10-80.77	First performed drying test then wetting test	1.6474	4.3158	With small amount of gravel, shrinkage cracks
A3	42.67-79.25	First performed drying test then wetting test	2.3579	2.7053	With small amount of gravel and silt, no shrinkage cracks
A4	7.62-44.20	First performed drying test then wetting test	5.7211	3.3158	With small amount of gravel, a few root fibers, shrinkage cracks
A5	44.20-80.77	First performed drying test then wetting test	1.4737	2.7053	A few root fibers, some gravel, shrinkage cracks
A6	42.67-79.25	First performed wetting test then drying test	2.7368	9.5421	A few gravel particles, shrinkage cracks
A7	0.00-33.53	First performed wetting test then drying test	10.5311	19.4737	A few root fibers, no visible cracks
A8	56.39-88.39	First performed wetting test then drying test	8.5789	31.8421	A crack formed near psychrometer during drilling caused by a gravel particle, shrinkage cracks
A9	0.00-38.40	First performed drying test then wetting test	5.3105	11.7895	Tiny longitudinal cracks along soil column before testing, shrinkage cracks

Table 3: Summary of Diffusion Coefficient Test Results (cont'd)

Sample No.	Depth (cm)	Testing Sequence	Drying Diffusion Coefficient $\alpha_{dry} \times 10^{-3}$ (cm^2/min)	Wetting Diffusion Coefficient $\alpha_{wet} \times 10^{-3}$ (cm^2/min)	Remarks
			SOIL B		
B1	0.00-38.40	First performed drying test then wetting test	2.1842	3.7474	A few small cracks along soil column before testing, small shrinkage cracks after drying test, a few root fibers
B2	0.00-44.20	First performed drying test then wetting test	5.8316	8.1842	Several cracks along soil column before testing, small shrinkage cracks after drying test, root fibers
B3	0.00-39.62	First performed wetting test then drying test	2.7053	3.7474	A few small cracks along soil column before testing, small shrinkage cracks after drying test, root fibers
B4	39.62-82.30	First performed drying test then wetting test	1.9053	6.8737	Several cracks along soil column before testing, no visible shrinkage cracks after drying test
B5	39.62-82.30	First performed drying test then wetting test	1.3474	5.3105	A few root fibers, no visible shrinkage cracks after drying process
B6	38.10-80.77	First performed drying test then wetting test	1.6474	4.7316	No visible shrinkage cracks after drying process

Table 3: Summary of Diffusion Coefficient Test Results (cont'd)

Sample No.	Depth (cm)	Testing Sequence	Drying Diffusion Coefficient $\alpha_{dry} \times 10^{-3}$ (cm^2/min)	Wetting Diffusion Coefficient $\alpha_{wet} \times 10^{-3}$ (cm^2/min)	Remarks
SOIL C					
C1		First performed drying test then wetting test	13.2105	15.2632	Dry, soft, silty, organic clay, easily breaks during sample preparation, no visible shrinkage cracks
C2		First performed drying test then wetting test	7.1053	8.9211	Dry, soft, silty, organic clay, easily breaks during sample preparation, no visible shrinkage cracks
C3		First performed drying test then wetting test	9.2105	14.7844	Dry, soft, silty, organic clay, easily breaks during sample preparation, no visible shrinkage cracks
C4		First performed drying test then wetting test	5.5263	7.6316	Dry, soft, silty, organic clay, easily breaks during sample preparation, no visible shrinkage cracks

Table 3: Summary of Diffusion Coefficient Test Results (cont'd)

Sample No.	**Depth (cm)**	**Testing Sequence**	**Drying Diffusion Coefficient $\alpha_{dry} \times 10^{-3}$ (cm^2/min)**	**Wetting Diffusion Coefficient $\alpha_{wet} \times 10^{-3}$ (cm^2/min)**	**Remarks**
			SOIL D		
D1		First performed drying test then wetting test	1.0158	1.0026	Wet, hard, clay soil, a few shrinkage cracks
D2		First performed drying test then wetting test	1.2816	1.0158	Wet, hard, clay soil, no visible shrinkage cracks
D3		First performed drying test then wetting test	1.5837	1.9316	Wet, hard, clay soil, no visible shrinkage cracks
D4		First performed drying test then wetting test	0.6316	1.4474	Wet, hard, clay soil, a few tiny roots, one shrinkage crack
D5		First performed drying test then wetting test	0.9368	1.2421	Wet, hard, clay soil, no visible shrinkage cracks
D6		First performed drying test then wetting test	0.5211	0.9526	Wet, hard, clay soil, shrinkage cracks (about 1 mm in diameter); largest crack compared to other specimens
D7		First performed drying test then wetting test	0.7895	1.5263	Wet, hard, clay soil, a few shrinkage cracks
D8		First performed drying test then wetting test	1.2421	1.7789	Wet, hard, clay soil, a few shrinkage cracks
D9		First performed drying test then wetting test	1.0526	1.3874	Wet, hard, clay soil, a few shrinkage cracks

Table 3: Summary of Diffusion Coefficient Test Results (cont'd)

Sample No.	**Depth (cm)**	**Testing Sequence**	**Drying Diffusion Coefficient $\alpha_{dry} \times 10^{-3}$ (cm^2/min)**	**Wetting Diffusion Coefficient $\alpha_{wet} \times 10^{-3}$ (cm^2/min)**	**Remarks**
SOIL E					
E1	3.05-42.67	First performed drying test then wetting test	3.4211	5.8947	With gravels, stiff soil, visible tiny cracks on the exposed end before testing,, a few shrinkage cracks
E2	0.00-44.20	First performed drying test then wetting test	1.8421	2.4211	With gravels, stiff soil, a few shrinkage cracks
E3	0.00-42.67	First performed drying test then wetting test	3.7368	5.0526	With gravels, stiff soil, a few shrinkage cracks
E4	0.00-38.25	First performed drying test then wetting test	4.1579	5.7474	With gravels, stiff soil, a few shrinkage cracks
E5	0.00-35.99	First performed drying test then wetting test	1.1842	1.6316	With gravels, stiff soil, a few shrinkage cracks
E6	0.00-30.48	First performed drying test then wetting test	2.9474	2.1053	With gravels, stiff soil, a few shrinkage cracks
E7	1.52-39.62	First performed drying test then wetting test	2.2632	2.7368	With gravels, stiff soil, a few shrinkage cracks

Table 3: Summary of Diffusion Coefficient Test Results (cont'd)

Sample No.	Depth (cm)	Testing Sequence	Drying Diffusion Coefficient $\alpha_{dry} \times 10^{-3}$ (cm^2/min)	Wetting Diffusion Coefficient $\alpha_{wet} \times 10^{-3}$ (cm^2/min)	Remarks
SOIL F					
F1	44.20-79.86	First performed drying test then wetting test	1.3884	1.8158	Soil with gravels, a few shrinkage cracks
F2	0.00-39.62	First performed drying test then wetting test	1.7368	1.9474	With gravels, stiff soil, no visible shrinkage cracks
F3	0.00-39.62	First performed drying test then wetting test	3.4737	2.0789	With gravels, stiff soil, one relatively large shrinkage crack compared to other specimens
F4	2.35-41.22	First performed drying test then wetting test	2.2632	3.3684	With gravels, stiff soil, a few shrinkage cracks
F5	0.00-32.86	First performed drying test then wetting test	1.2105	1.6316	With gravels, stiff soil, a few shrinkage cracks

CHAPTER V

CONCLUSIONS

The determination of unsaturated moisture diffusivity of a soil is important for design of pavements, embankments, slopes, dams, clay liners, and other agricultural and soil science applications. The critical parameter that will control the rate at which moisture will move in an unsaturated soil is the soil diffusivity coefficient. Mitchell (1979) provided a simple, economical and reliable test method for estimating the wetting and drying diffusivity parameters on a routine basis in a geotechnical laboratory. This provided a relatively rapid framework to study the hysteresis properties of a soil mass.

The diffusivity measurements are summarized as follows:

Soil	**Drying Diffusion Coefficient α_{dry} x 10^{-3} (cm^2/min)**	**Wetting Diffusion Coefficient α_{wet} x 10^{-3} (cm^2/min)**
A	1.47-10.53	2.70-12.72
B	1.34-5.83	3.74-8.18
C	5.53-13.21	7.63-15.26
D	0.63-1.28	0.95-1.93
E	1.18-4.16	1.63-5.89
F	1.21-3.47	1.63-3.37

Overall the diffusivity data suggests the following:

- For most soil specimens tested, α_{wet} values are generally higher than α_{dry} values by a magnitude of 1-2.
- Soils with significant cracks have much higher α_{wet} values.
- Hard/stiff clay soils tend to have a smaller α values than silty/sandy soils.
- Soils obtained from deeper depths from the ground surface tend to have a smaller hysteresis effect than the soils at shallower depths.

The proposed testing method and equipment provide a strong tool for realistic characterization of diffusion properties in soils. Finally, it has been noted that cracks in the soil, vegetative influence such as root fibers, soil densification (soft or hard), soil stratification and soil type contribute to the hysteresis between the drying and wetting diffusion parameters.

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APPENDIX A

DIFFUSION COEFFICIENT VALUES AND CURVES

Specimen No.: **SOIL A1**

Drying Test

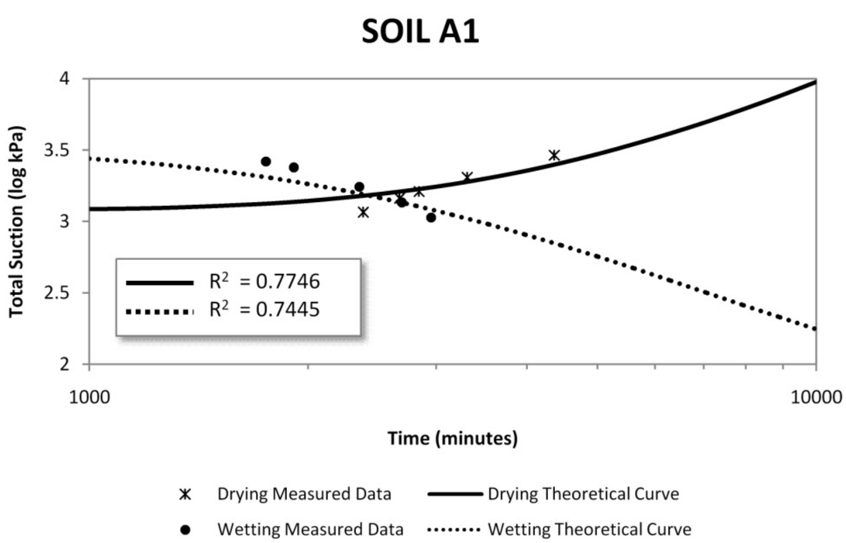
Evaporation Coefficient:	$0.54\ cm^{-1}$	
Atmospheric Suction:	5.21 log kPa	
Initial Suction:	3.09 log kPa	
Psychrometer Location:	4.0 cm	
Sample Length:	15.0 cm	
Suction Measurements:	Time (min)	Suction (log kPa)
	2380	3.066
	2670	3.164
	2840	3.212
	3310	3.309
	4360	3.466

Drying Diffusion Coefficient: $\mathbf{8.16x10^{-3}\ cm^2/min}$

Wetting Test

Soaking Suction:	1.75 log kPa	
Initial Suction:	3.50 log kPa	
Psychrometer Location:	4.0 cm	
Sample Length:	15.0 cm	
Suction Measurements:	Time (min)	Suction (log kPa)
	1750	3.422
	1910	3.379
	2350	3.245
	2690	3.134
	2950	3.029

Wetting Diffusion Coefficient: $\mathbf{12.72x10^{-3}\ cm^2/min}$

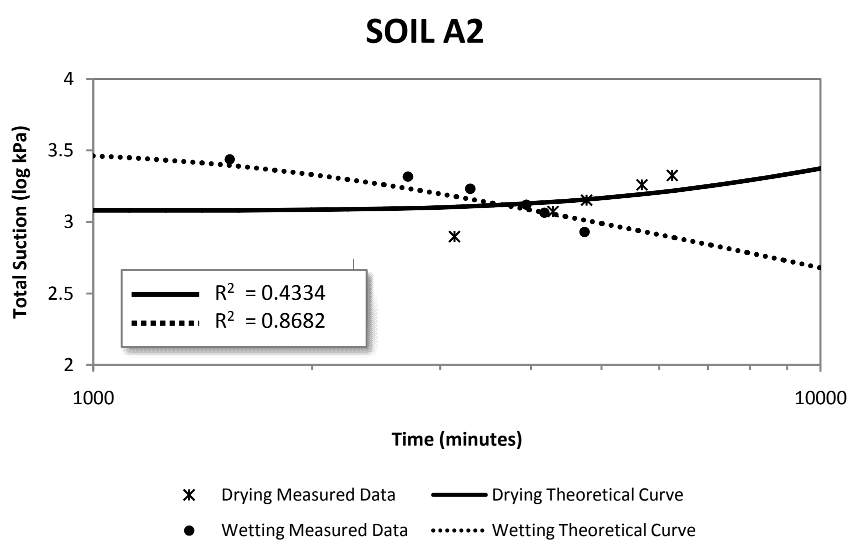


Specimen No.: **SOIL A2**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.21 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	3.09 log kPa		Initial Suction:	3.50 log kPa	
Psychrometer Location:	8.0 cm		Psychrometer Location:	8.0 cm	
Sample Length:	15.0 cm		Sample Length:	15.0 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	3140	2.897		1540	3.440
	4290	3.073		2710	3.319
	4770	3.154		3300	3.232
	5680	3.261		3940	3.122
	6250	3.325		4170	3.066
				4740	2.931

Drying Diffusion Coefficient: **1.65x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **4.32x10^{-3} cm^2/min**

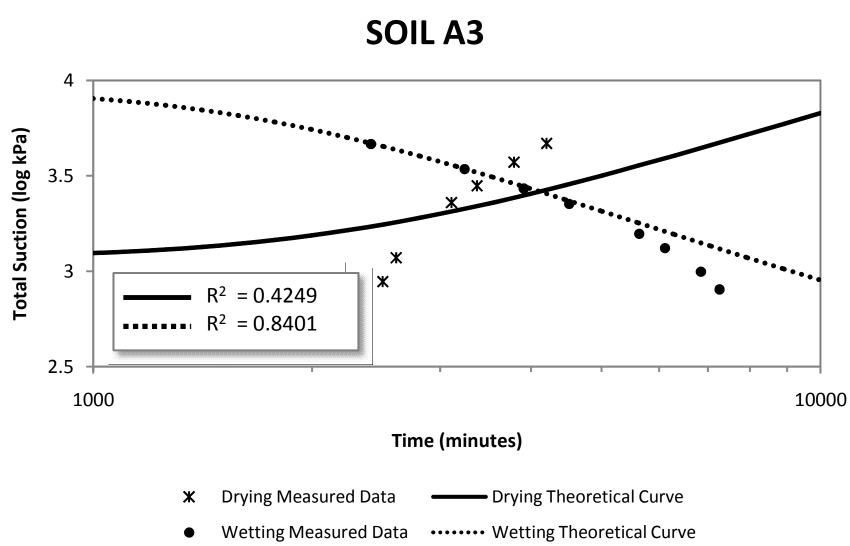


Specimen No.: **SOIL A3**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.22 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	3.09 log kPa		Initial Suction:	3.95 log kPa	
Psychrometer Location:	13.9 cm		Psychrometer Location:	13.9 cm	
Sample Length:	18.9 cm		Sample Length:	18.9 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	2500	2.946		2410	3.668
	2610	3.071		3240	3.536
	3110	3.360		3910	3.433
	3370	3.448		4510	3.354
	3790	3.571		5630	3.197
	4200	3.670		6110	3.122
				6850	2.999
				7260	2.905

Drying Diffusion Coefficient: **2.36×10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **2.71×10^{-3} cm^2/min**

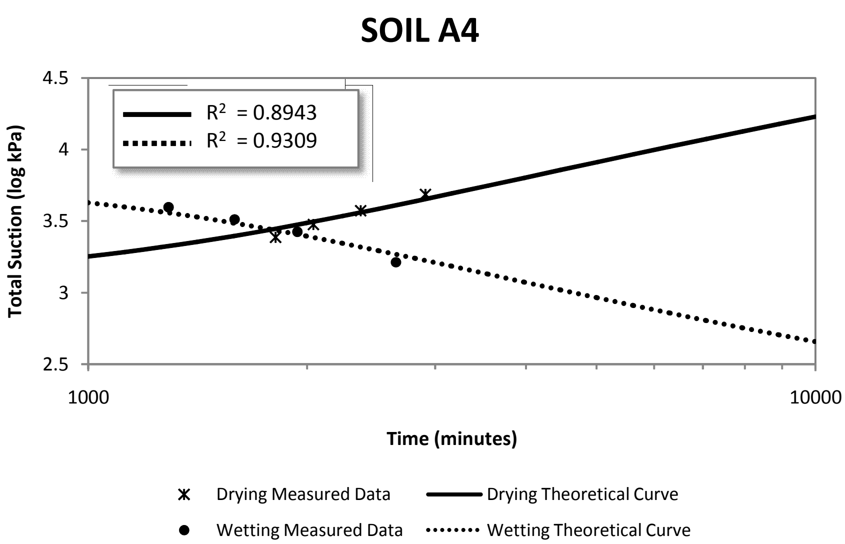


Specimen No.: SOIL A4

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.23 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	3.13 log kPa		Initial Suction:	3.74 log kPa	
Psychrometer Location:	13.4 cm		Psychrometer Location:	13.4 cm	
Sample Length:	18.4 cm		Sample Length:	18.4 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	1810	3.387		1290	3.597
	2040	3.476		1590	3.514
	2370	3.573		1940	3.425
	2910	3.686		2650	3.214

Drying Diffusion Coefficient: $\mathbf{5.72 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{3.32 \times 10^{-3}\ cm^2/min}$

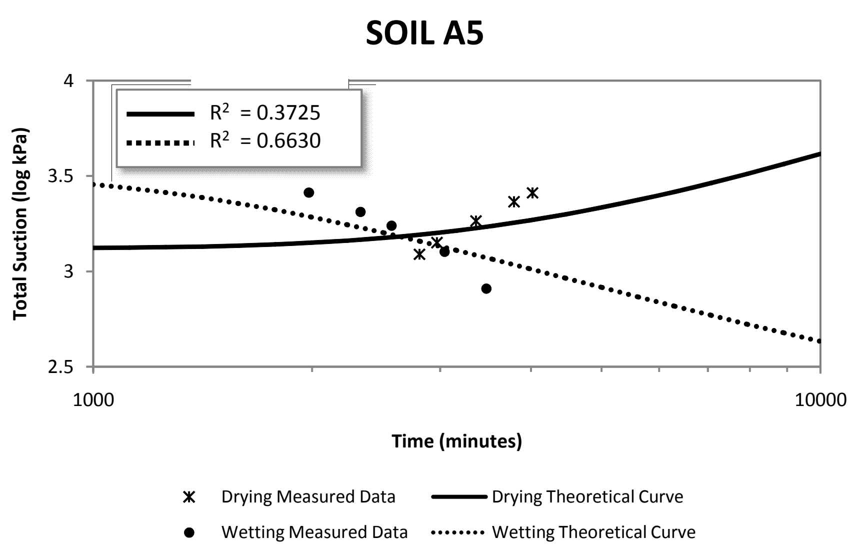


Specimen No.: **SOIL A5**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.29 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	3.13 log kPa		Initial Suction:	3.52 log kPa	
Psychrometer Location:	14.1 cm		Psychrometer Location:	14.1 cm	
Sample Length:	19.1 cm		Sample Length:	19.1 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	2810	3.091		1980	3.414
	2970	3.151		2330	3.313
	3360	3.266		2570	3.241
	3790	3.365		3040	3.104
	4020	3.413		3470	2.911

Drying Diffusion Coefficient: $\mathbf{1.47 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{2.71 \times 10^{-3}\ cm^2/min}$

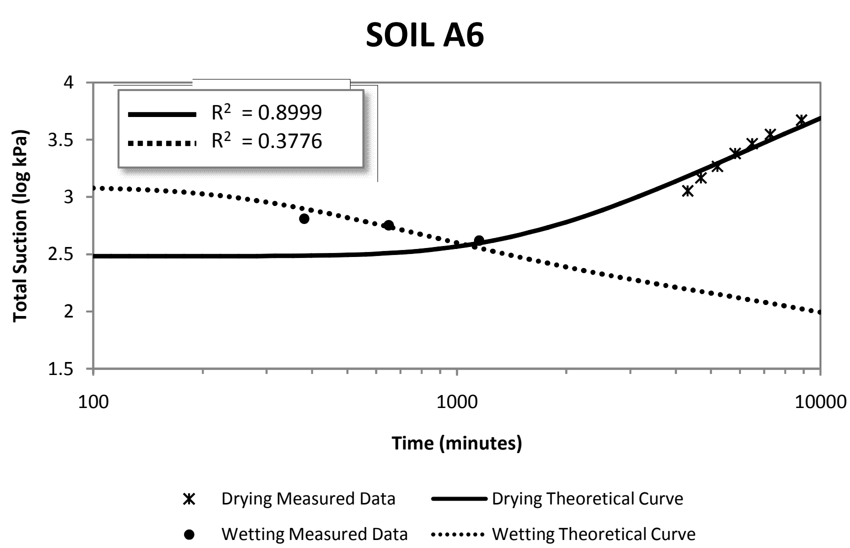


Specimen No.: **SOIL A6**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.22 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.50 log kPa		Initial Suction:	3.09 log kPa	
Psychrometer Location:	11.4 cm		Psychrometer Location:	11.4 cm	
Sample Length:	15.4 cm		Sample Length:	15.4 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	4310	3.053		380	2.810
	4690	3.168		650	2.753
	5210	3.269		1150	2.619
	5830	3.380			
	6490	3.468			
	7270	3.549			
	8860	3.671			

Drying Diffusion Coefficient: **$2.74\times10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$9.54\times10^{-3}\ cm^2/min$**

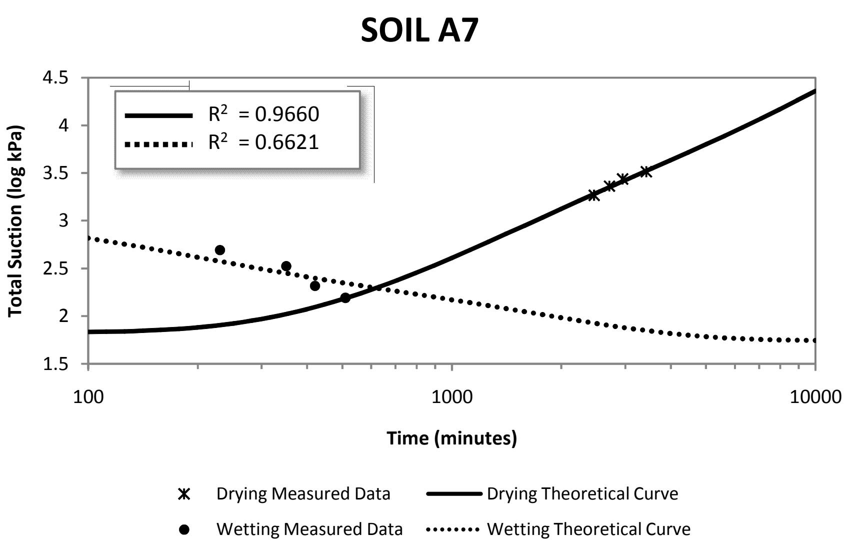


Specimen No.: **SOIL A7**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.21 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.85 log kPa		Initial Suction:	2.55 log kPa	
Psychrometer Location:	10.2 cm		Psychrometer Location:	10.2 cm	
Sample Length:	14.2 cm		Sample Length:	14.2 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	2460	3.266		230	2.695
	2710	3.365		350	2.526
	2950	3.438		420	2.319
	3430	3.514		510	2.191

Drying Diffusion Coefficient: **$10.53 \times 10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$19.47 \times 10^{-3}\ cm^2/min$**



Specimen No.: **SOIL A8**

Drying Test

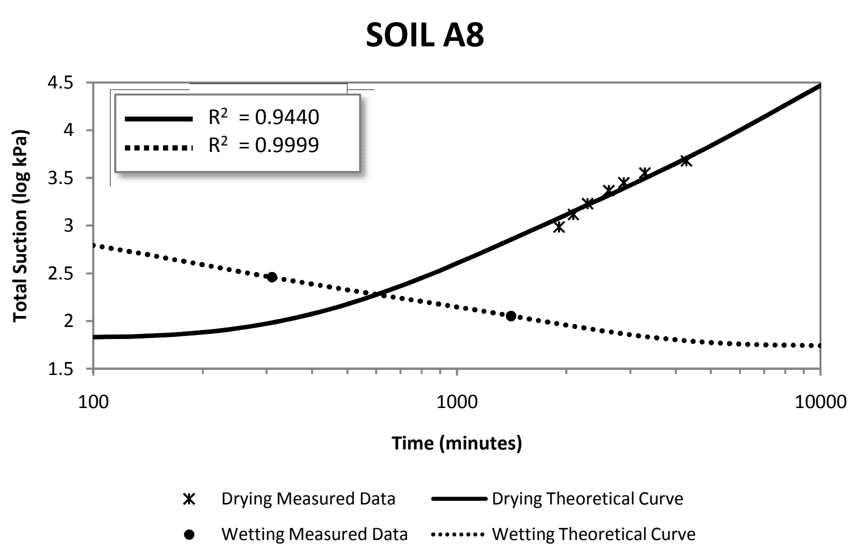
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	5.20 log kPa	
Initial Suction:	1.83 log kPa	
Psychrometer Location:	7.7 cm	
Sample Length:	11.2 cm	
Suction Measurements:	Time (min)	Suction (log kPa)
	1910	2.986
	2090	3.116
	2290	3.229
	2620	3.370
	2880	3.452
	3290	3.554
	4280	3.680

Drying Diffusion Coefficient: **8.58x10^{-3} cm^2/min**

Wetting Test

Soaking Suction:	1.75 log kPa	
Initial Suction:	3.01 log kPa	
Psychrometer Location:	7.7 cm	
Sample Length:	11.2 cm	
Suction Measurements:	Time (min)	Suction (log kPa)
	310	2.459
	1410	2.052

Wetting Diffusion Coefficient: **31.84x10^{-3} cm^2/min**

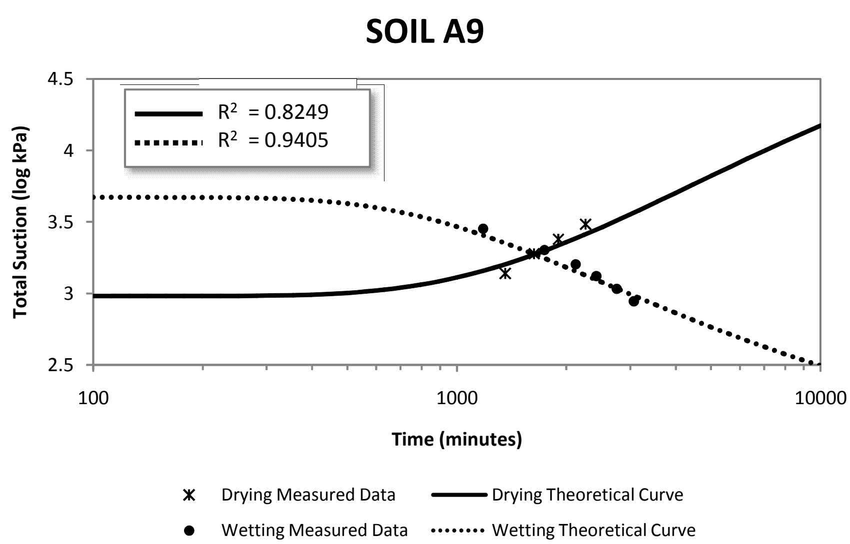


Specimen No.: **SOIL A9**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.32 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	3.00 log kPa		Initial Suction:	3.68 log kPa	
Psychrometer Location:	14.5 cm		Psychrometer Location:	14.5 cm	
Sample Length:	19.5 cm		Sample Length:	19.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	1360	3.140		1180	3.454
	1630	3.279		1740	3.305
	1900	3.381		2120	3.205
	2260	3.486		2420	3.123
				2750	3.034
				3070	2.945

Drying Diffusion Coefficient: **5.31×10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **11.79×10^{-3} cm^2/min**

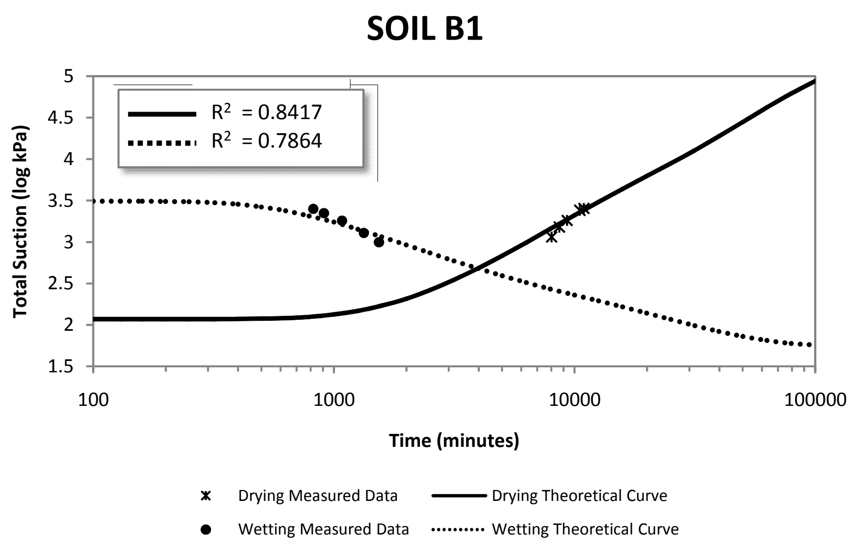


Specimen No.: **SOIL B1**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.27 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.09 log kPa		Initial Suction:	3.50 log kPa	
Psychrometer Location:	11.1 cm		Psychrometer Location:	11.1 cm	
Sample Length:	15.1 cm		Sample Length:	15.1 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	8020	3.064		820	3.403
	8650	3.180		910	3.351
	9300	3.263		1080	3.259
	10520	3.383		1330	3.112
	10920	3.409		1540	2.999

Drying Diffusion Coefficient: **$2.18\times10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$3.75\times10^{-3}\ cm^2/min$**

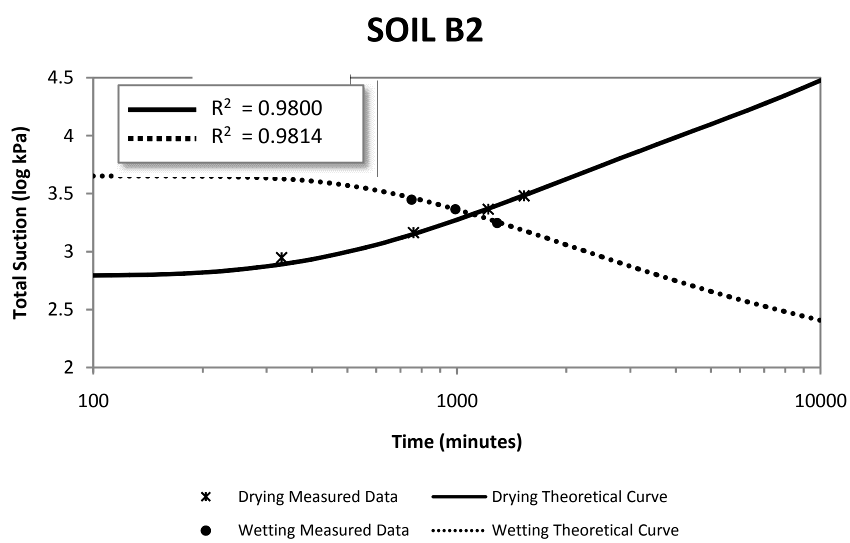


Specimen No.: **SOIL B2**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.21 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.80 log kPa		Initial Suction:	3.66 log kPa	
Psychrometer Location:	8.6 cm		Psychrometer Location:	8.6 cm	
Sample Length:	11.6 cm		Sample Length:	11.6 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	330	2.947		750	3.449
	760	3.163		990	3.368
	1220	3.368		1290	3.249
	1530	3.481			

Drying Diffusion Coefficient: **$5.83\text{x}10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$8.18\text{x}10^{-3}\ cm^2/min$**

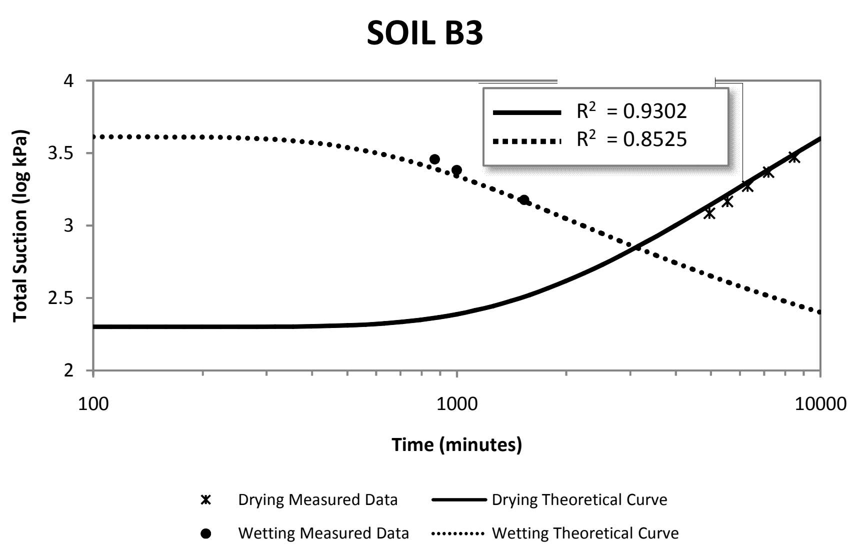


Specimen No.: **SOIL B3**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.27 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.32 log kPa		Initial Suction:	3.62 log kPa	
Psychrometer Location:	10.8 cm		Psychrometer Location:	10.8 cm	
Sample Length:	14.8 cm		Sample Length:	14.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	4950	3.085		870	3.459
	5550	3.166		1000	3.384
	6310	3.271		1530	3.179
	7190	3.368			
	8480	3.473			

Drying Diffusion Coefficient: $\mathbf{2.70 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{3.57 \times 10^{-3}\ cm^2/min}$

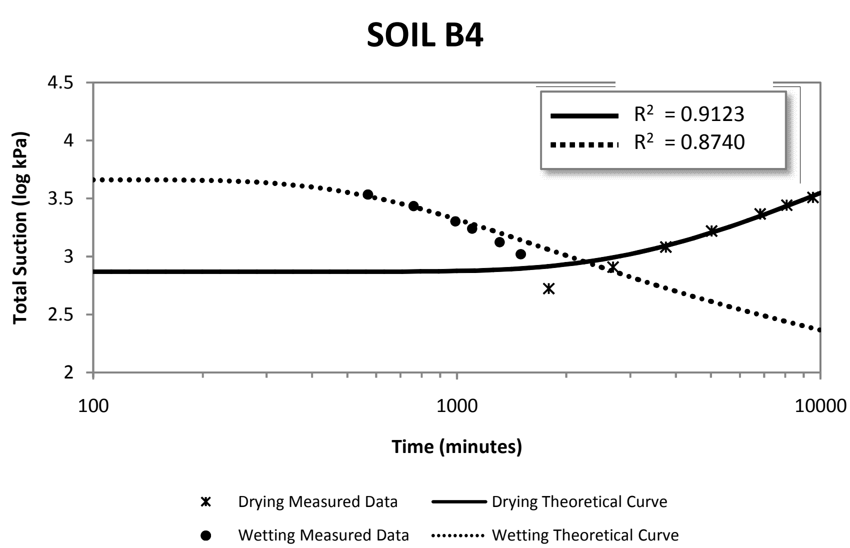


Specimen No.: **SOIL B4**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.26 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.88 log kPa		Initial Suction:	3.67 log kPa	
Psychrometer Location:	13.8 cm		Psychrometer Location:	13.8 cm	
Sample Length:	18.8 cm		Sample Length:	18.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	1790	2.726		570	3.536
	2690	2.908		760	3.437
	3760	3.082		990	3.304
	5020	3.220		1100	3.242
	6830	3.366		1310	3.126
	8070	3.443		1500	3.022
	9540	3.510			

Drying Diffusion Coefficient: $\mathbf{1.90x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{6.87x10^{-3}\ cm^2/min}$

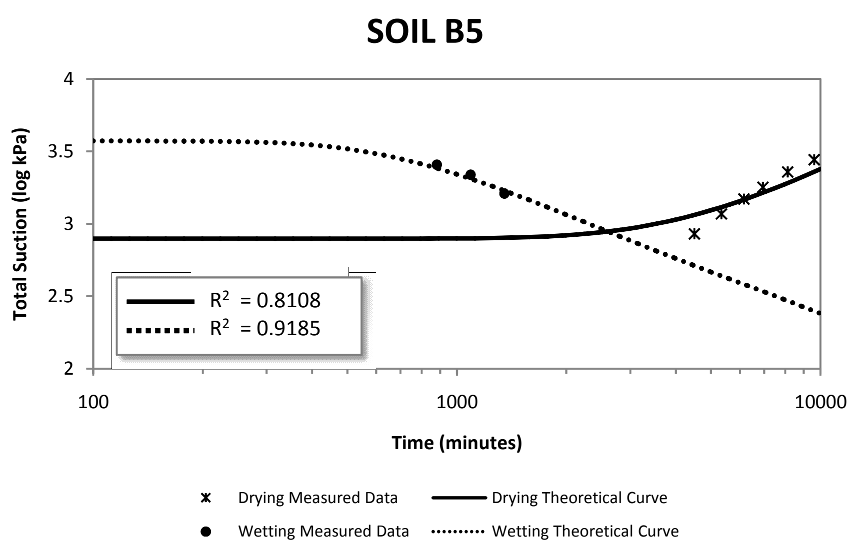


Specimen No.: **SOIL B5**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.20 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.91 log kPa		Initial Suction:	3.58 log kPa	
Psychrometer Location:	9.1 cm		Psychrometer Location:	9.1 cm	
Sample Length:	14.1 cm		Sample Length:	14.1 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	4500	2.931		880	3.408
	5340	3.070		1090	3.339
	6160	3.171		1350	3.209
	6950	3.253			
	8130	3.358			
	9610	3.443			

Drying Diffusion Coefficient: $\mathbf{1.35x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{5.31x10^{-3}\ cm^2/min}$

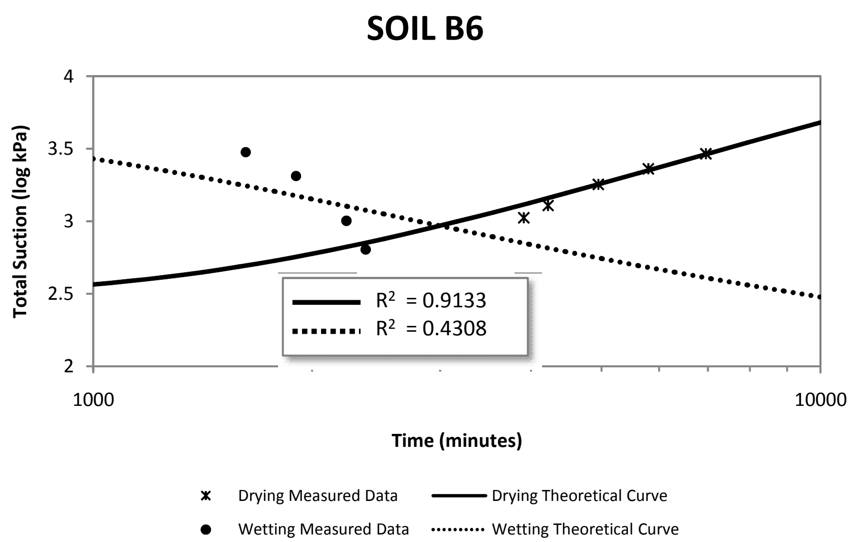


Specimen No.: **SOIL B6**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.36 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.97 log kPa		Initial Suction:	3.64 log kPa	
Psychrometer Location:	13.6 cm		Psychrometer Location:	13.6 cm	
Sample Length:	18.6 cm		Sample Length:	18.6 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	3910	3.024		1620	3.478
	4220	3.110		1900	3.314
	4950	3.254		2230	3.003
	5800	3.361			
	6960	3.465			

Drying Diffusion Coefficient: **$1.65\times10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$4.73\times10^{-3}\ cm^2/min$**

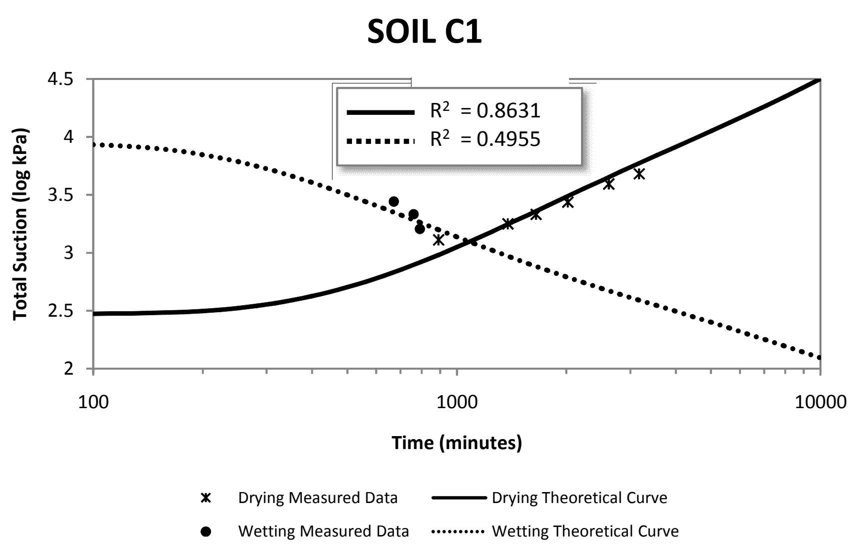


Specimen No.: **SOIL C1**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.29 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.48 log kPa		Initial Suction:	3.95 log kPa	
Psychrometer Location:	12.4 cm		Psychrometer Location:	12.4 cm	
Sample Length:	17.4 cm		Sample Length:	17.4 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	890	3.111		670	3.442
	1380	3.250		760	3.335
	1650	3.333		790	3.207
	2020	3.439			
	2620	3.594			
	3170	3.683			

Drying Diffusion Coefficient: **13.21x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **15.26x10^{-3} cm^2/min**

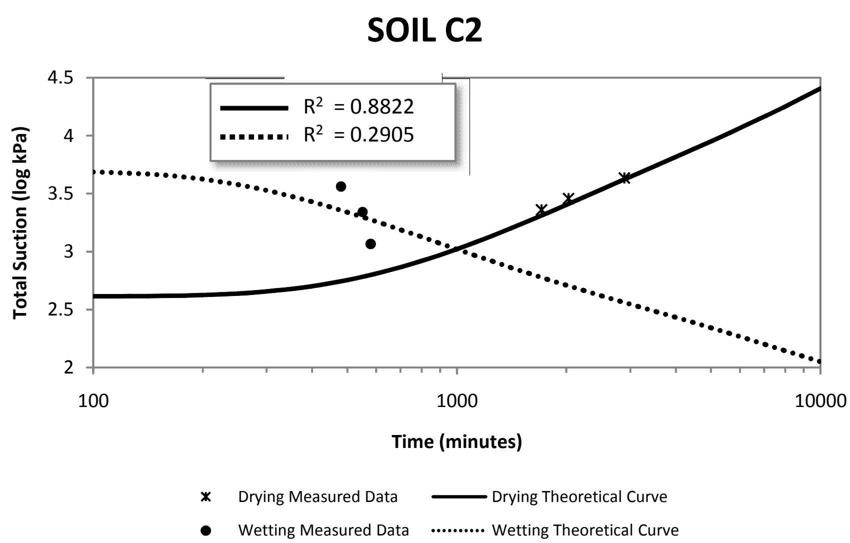


Specimen No.: **SOIL C2**

Drying Test				Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$					
Atmospheric Suction:	5.29 log kPa			Soaking Suction:	1.75 log kPa	
Initial Suction:	2.63 log kPa			Initial Suction:	3.70 log kPa	
Psychrometer Location:	8.9 cm			Psychrometer Location:	8.9 cm	
Sample Length:	12.9 cm			Sample Length:	12.9 cm	
Suction Measurements:	Time (min)	Suction (log kPa)		Suction Measurements:	Time (min)	Suction (log kPa)
	1710	3.360			480	3.561
	2030	3.457			550	3.344
	2890	3.634			580	3.066

Drying Diffusion Coefficient: $\mathbf{7.11 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{8.92 \times 10^{-3}\ cm^2/min}$

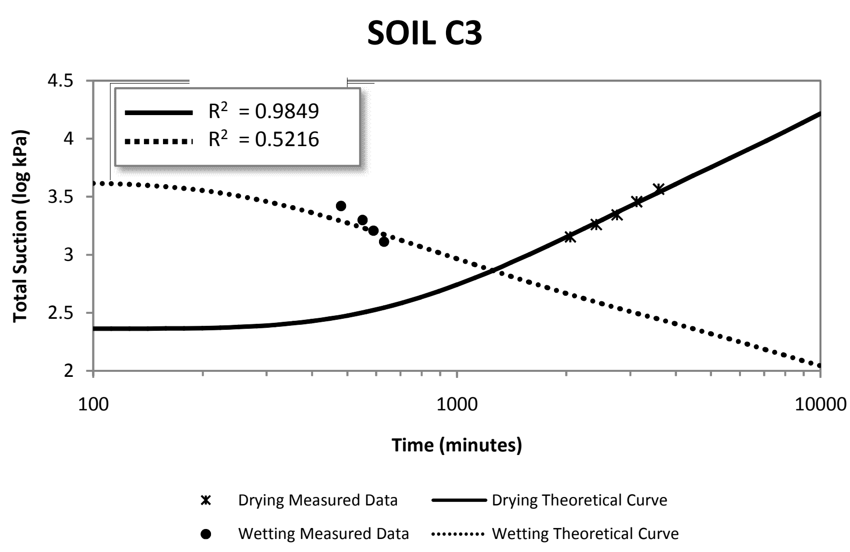


Specimen No.: **SOIL C3**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.29 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.38 log kPa		Initial Suction:	3.65 log kPa	
Psychrometer Location:	11.5 cm		Psychrometer Location:	11.5 cm	
Sample Length:	16.5 cm		Sample Length:	16.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	2050	3.156		480	3.420
	2420	3.261		550	3.299
	2760	3.346		590	3.210
	3120	3.458		630	3.114
	3590	3.565			

Drying Diffusion Coefficient: $\mathbf{9.21 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{14.21 \times 10^{-3}\ cm^2/min}$

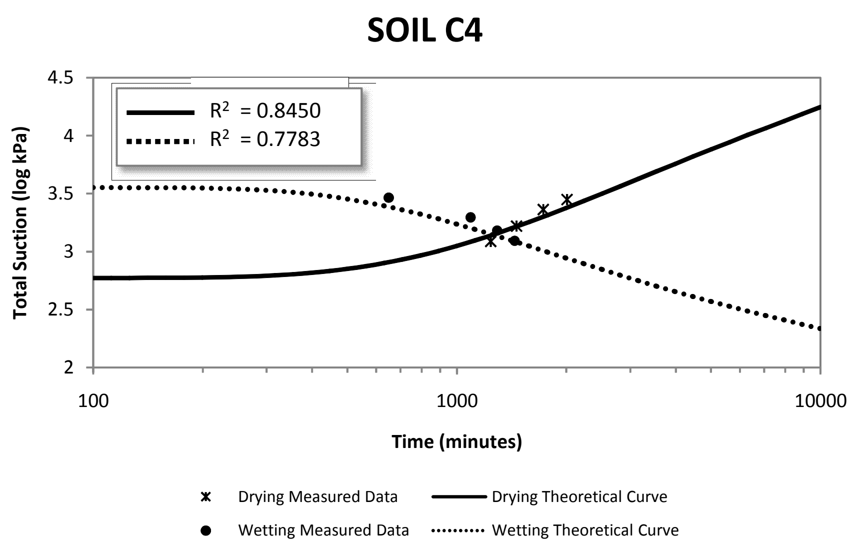


Specimen No.: **SOIL C4**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.28 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.79 log kPa		Initial Suction:	3.56 log kPa	
Psychrometer Location:	11.1 cm		Psychrometer Location:	11.1 cm	
Sample Length:	15.1 cm		Sample Length:	15.1 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	1240	3.088		650	3.467
	1460	3.220		1090	3.295
	1730	3.363		1290	3.184
	2010	3.449		1440	3.095

Drying Diffusion Coefficient: **5.53x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **7.63x10^{-3} cm^2/min**

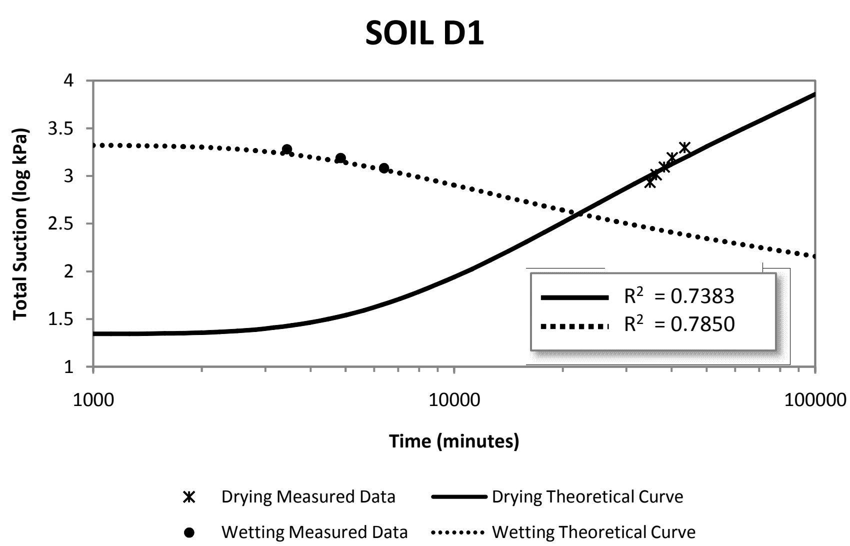


Specimen No.: **SOIL D1**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.25 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.35 log kPa		Initial Suction:	3.33 log kPa	
Psychrometer Location:	14.6 cm		Psychrometer Location:	14.6 cm	
Sample Length:	19.6 cm		Sample Length:	19.6 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	34810	2.935		3440	3.282
	36260	3.013		4850	3.190
	38130	3.096		6390	3.081
	40130	3.194			
	43470	3.298			

Drying Diffusion Coefficient: **$1.02\times10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$1.00\times10^{-3}\ cm^2/min$**

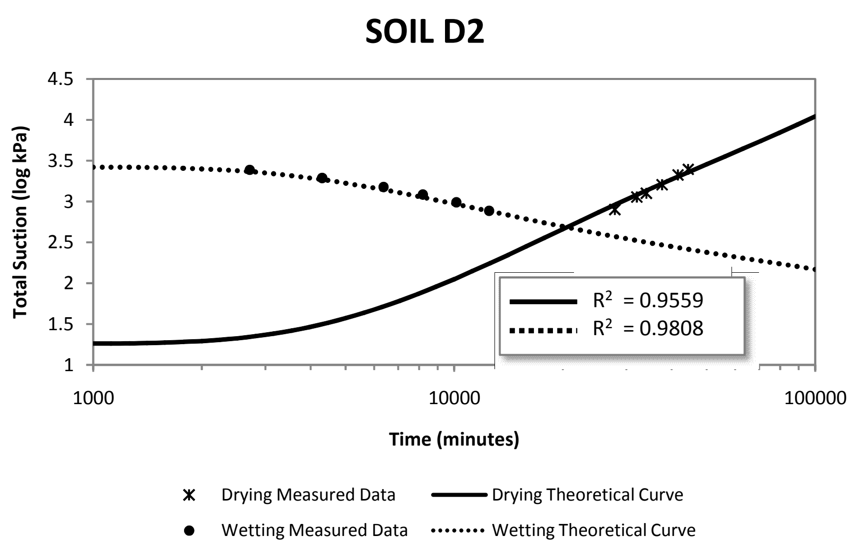


Specimen No.: **SOIL D2**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.24 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.27 log kPa		Initial Suction:	3.43 log kPa	
Psychrometer Location:	13.7 cm		Psychrometer Location:	13.7 cm	
Sample Length:	18.7 cm		Sample Length:	18.7 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	27870	2.901		2710	3.389
	32060	3.054		4310	3.287
	34070	3.101		6370	3.177
	37690	3.205		8180	3.085
	41630	3.325		10130	2.990
	44440	3.397		12480	2.886

Drying Diffusion Coefficient: **$1.28x10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$1.02x10^{-3}\ cm^2/min$**

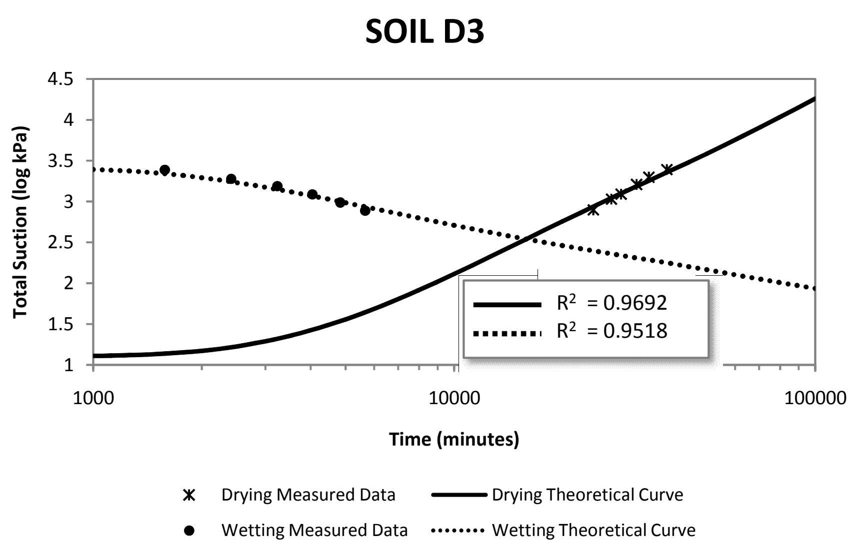


Specimen No.: **SOIL D3**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.24 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.12 log kPa		Initial Suction:	3.42 log kPa	
Psychrometer Location:	12.5 cm		Psychrometer Location:	12.5 cm	
Sample Length:	17.5 cm		Sample Length:	17.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	24290	2.900		1580	3.390
	27230	3.032		2410	3.279
	29010	3.093		3240	3.191
	32030	3.209		4050	3.090
	34640	3.297		4830	2.987
	38850	3.394		5670	2.890

Drying Diffusion Coefficient: **$1.58\text{x}10^{-3}$ cm^2/min**

Wetting Diffusion Coefficient: **$1.93\text{x}10^{-3}$ cm^2/min**

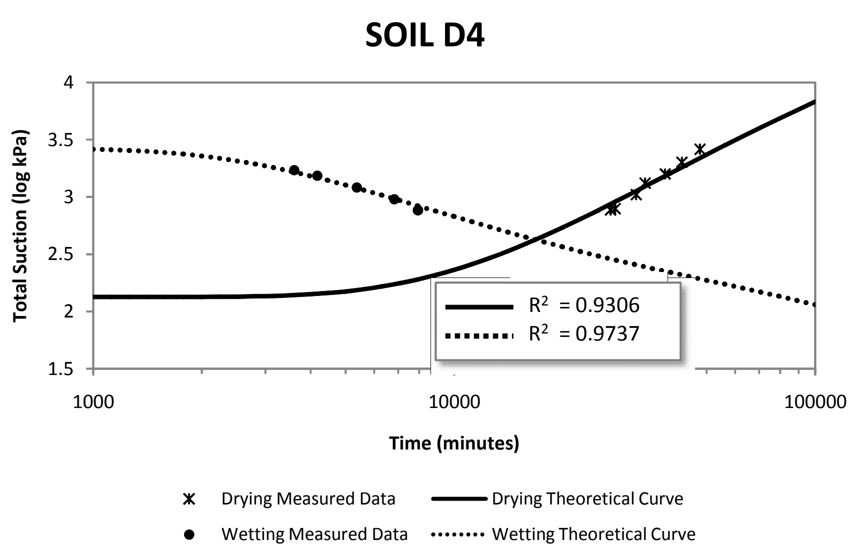


Specimen No.: **SOIL D4**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.25 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.14 log kPa		Initial Suction:	3.43 log kPa	
Psychrometer Location:	13.9 cm		Psychrometer Location:	13.9 cm	
Sample Length:	18.9 cm		Sample Length:	18.9 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	27110	2.887		3600	3.236
	27910	2.897		4170	3.188
	31890	3.021		5370	3.085
	33810	3.121		6820	2.981
	38380	3.203		7940	2.884
	42760	3.306			
	47900	3.417			

Drying Diffusion Coefficient: $\mathbf{0.632x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{1.45x10^{-3}\ cm^2/min}$

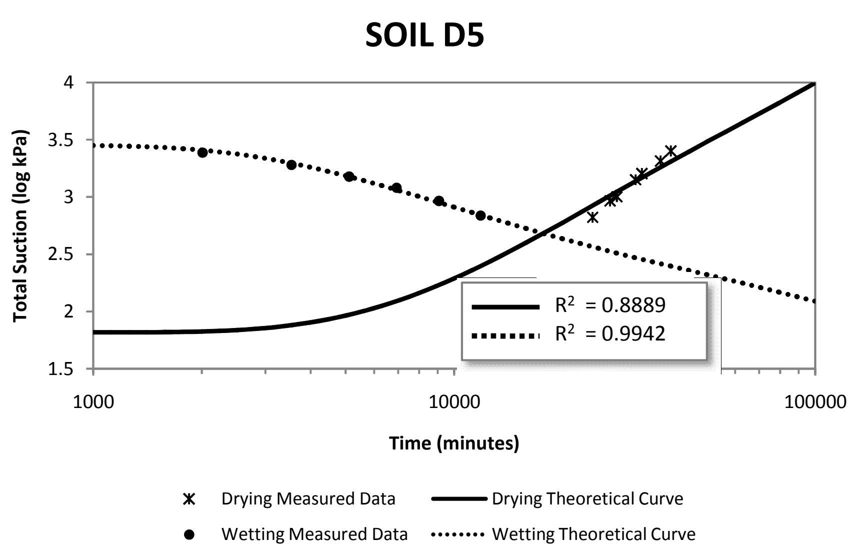


Specimen No.: **SOIL D5**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.24 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.83 log kPa		Initial Suction:	3.46 log kPa	
Psychrometer Location:	12.5 cm		Psychrometer Location:	15.5 cm	
Sample Length:	17.5 cm		Sample Length:	17.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	24160	2.824		2010	3.389
	27050	2.965		3540	3.281
	28200	3.004		5120	3.178
	31830	3.153		6920	3.083
	33120	3.204		9080	2.965
	37330	3.314		11820	2.839
	39840	3.402			

Drying Diffusion Coefficient: $\mathbf{0.937x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{1.24x10^{-3}\ cm^2/min}$

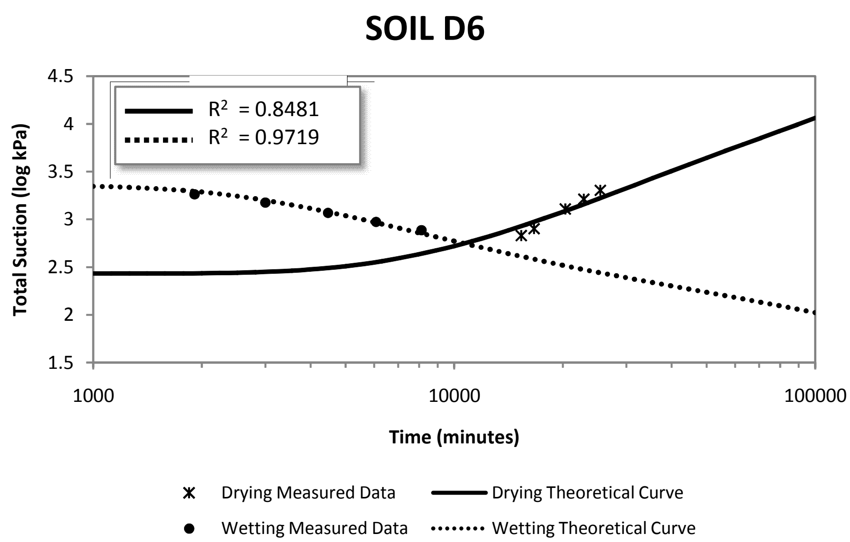


Specimen No.: **SOIL D6**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.24 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.45 log kPa		Initial Suction:	4.36 log kPa	
Psychrometer Location:	10.5 cm		Psychrometer Location:	10.5 cm	
Sample Length:	14.5 cm		Sample Length:	14.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	15350	2.830		1910	3.265
	16640	2.905		3000	3.178
	20320	3.108		4470	3.071
	22860	3.215		6070	2.975
	25410	3.307		8120	2.888

Drying Diffusion Coefficient: $\mathbf{0.521 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{0.953 \times 10^{-3}\ cm^2/min}$

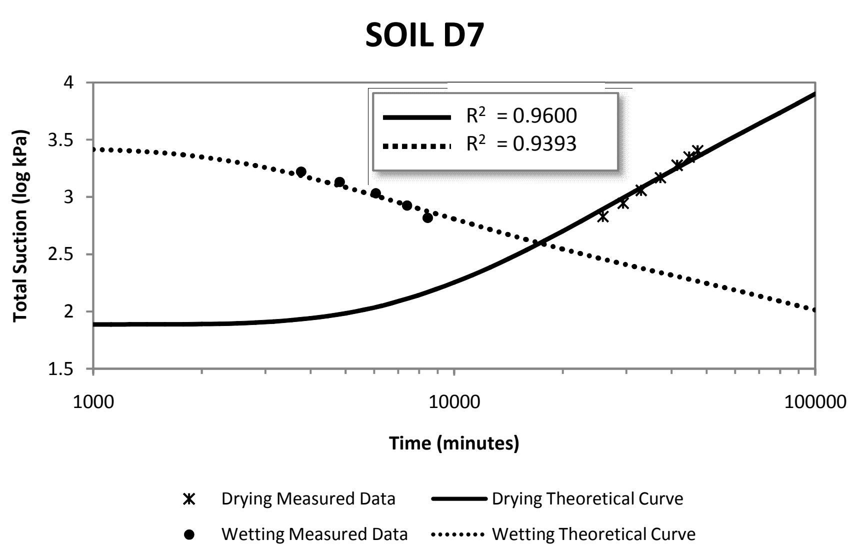


Specimen No.: **SOIL D7**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.25 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.90 log kPa		Initial Suction:	3.43 log kPa	
Psychrometer Location:	12.5 cm		Psychrometer Location:	12.5 cm	
Sample Length:	17.5 cm		Sample Length:	17.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	25800	2.831		3770	3.222
	29350	2.947		4820	3.133
	32920	3.057		6060	3.034
	37240	3.170		7400	2.927
	41480	3.277		8450	2.820
	44770	3.349			
	47230	3.404			

Drying Diffusion Coefficient: $\mathbf{0.789 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{1.53 \times 10^{-3}\ cm^2/min}$

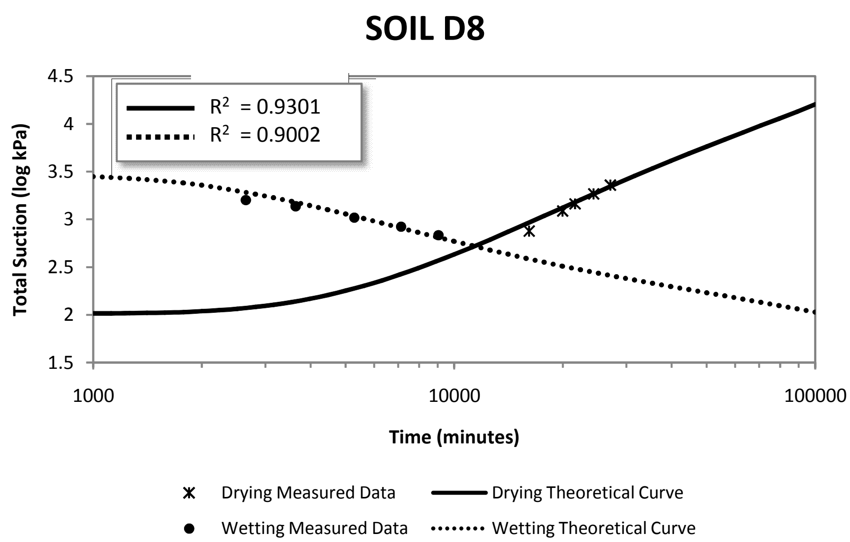


Specimen No.: **SOIL D8**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.24 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.03 log kPa		Initial Suction:	3.47 log kPa	
Psychrometer Location:	15.4 cm		Psychrometer Location:	15.4 cm	
Sample Length:	20.4 cm		Sample Length:	20.4 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	16110	2.878		2650	3.205
	19950	3.088		3640	3.137
	21620	3.165		5280	3.021
	24320	3.267		7120	2.926
	27070	3.359		9050	2.836

Drying Diffusion Coefficient: **$1.24\times10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$1.78\times10^{-3}\ cm^2/min$**

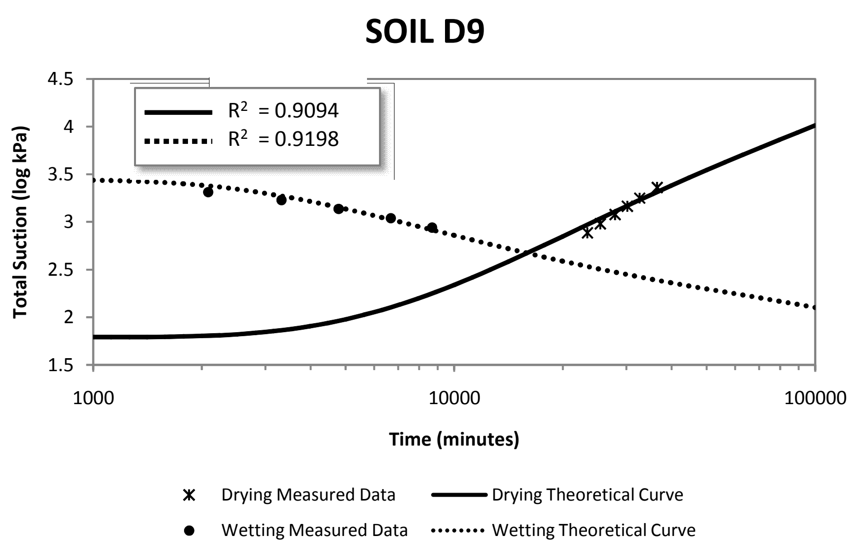


Specimen No.: **SOIL D9**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.23 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.80 log kPa		Initial Suction:	3.45 log kPa	
Psychrometer Location:	15.7 cm		Psychrometer Location:	15.7 cm	
Sample Length:	20.7 cm		Sample Length:	20.7 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	23360	2.886		2080	3.314
	25410	2.980		3320	3.229
	27920	3.077		4790	3.139
	30180	3.164		6670	3.042
	32620	3.252		8680	2.940
	36470	3.361			

Drying Diffusion Coefficient: **1.05×10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **1.39×10^{-3} cm^2/min**

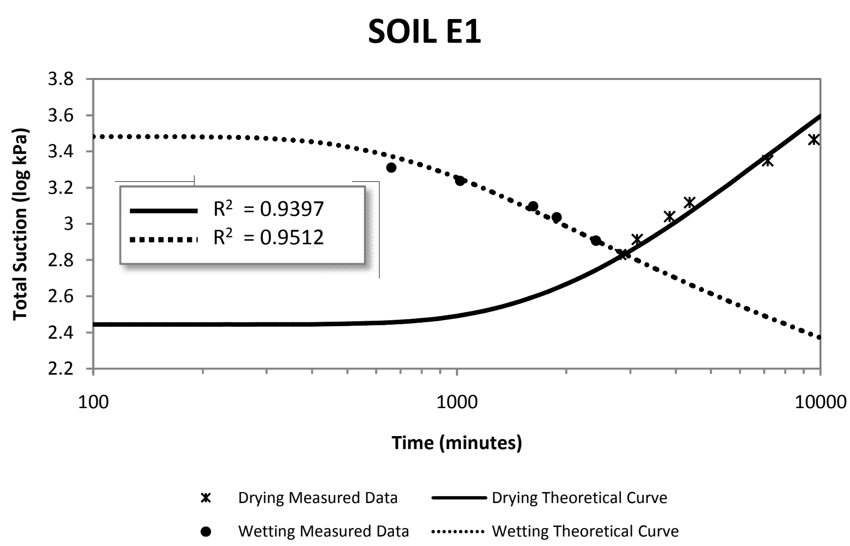


Specimen No.: **SOIL E1**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.30 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.46 log kPa		Initial Suction:	3.49 log kPa	
Psychrometer Location:	12.0 cm		Psychrometer Location:	12.0 cm	
Sample Length:	17.2 cm		Sample Length:	17.2 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	2820	2.832		660	3.312
	3130	2.915		1020	3.239
	3850	3.040		1620	3.099
	4370	3.118		1880	3.038
	7160	3.349		2410	2.907
	9600	3.467			

Drying Diffusion Coefficient: $\mathbf{3.42 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{5.89 \times 10^{-3}\ cm^2/min}$

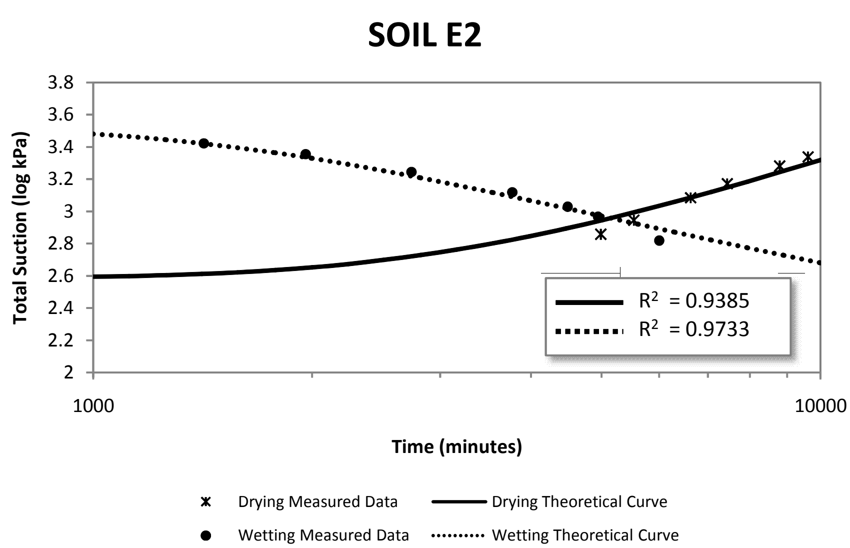


Specimen No.: **SOIL E2**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.23 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.60 log kPa		Initial Suction:	3.53 log kPa	
Psychrometer Location:	13.8 cm		Psychrometer Location:	13.8 cm	
Sample Length:	18.8 cm		Sample Length:	18.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	4990	2.858		1420	3.424
	5540	2.945		1960	3.357
	6630	3.086		2740	3.246
	7440	3.173		3770	3.120
	8790	3.281		4490	3.029
	9610	3.340		4940	2.967
	11540	3.466		6000	2.819

Drying Diffusion Coefficient: **$1.84\times10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$2.42\times10^{-3}\ cm^2/min$**

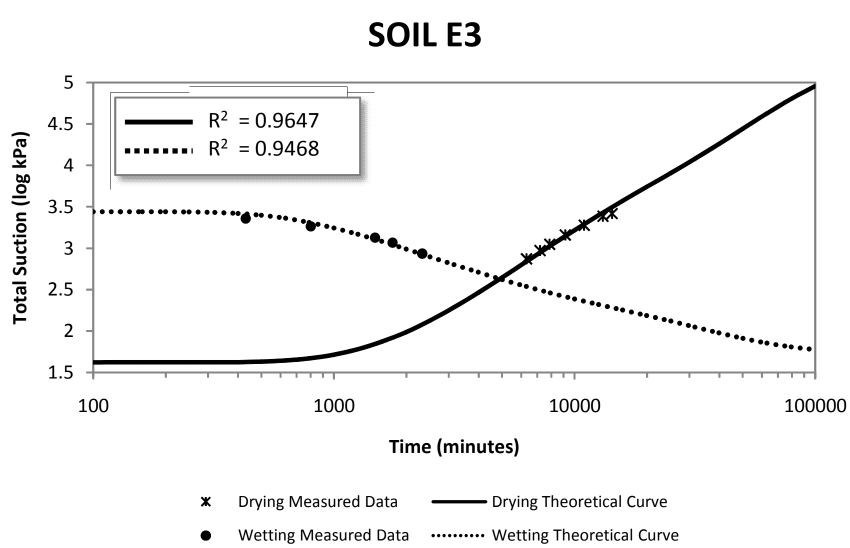


Specimen No.: **SOIL E3**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.28 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.64 log kPa		Initial Suction:	3.45 log kPa	
Psychrometer Location:	14.9 cm		Psychrometer Location:	14.9 cm	
Sample Length:	19.9 cm		Sample Length:	19.9 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	6320	2.872		430	3.358
	7190	2.971		800	3.265
	7870	3.046		1480	3.130
	9160	3.159		1750	3.069
	10950	3.276		2330	2.934
	13100	3.386			
	14330	3.421			

Drying Diffusion Coefficient: $\mathbf{3.74 \times 10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{5.05 \times 10^{-3}\ cm^2/min}$

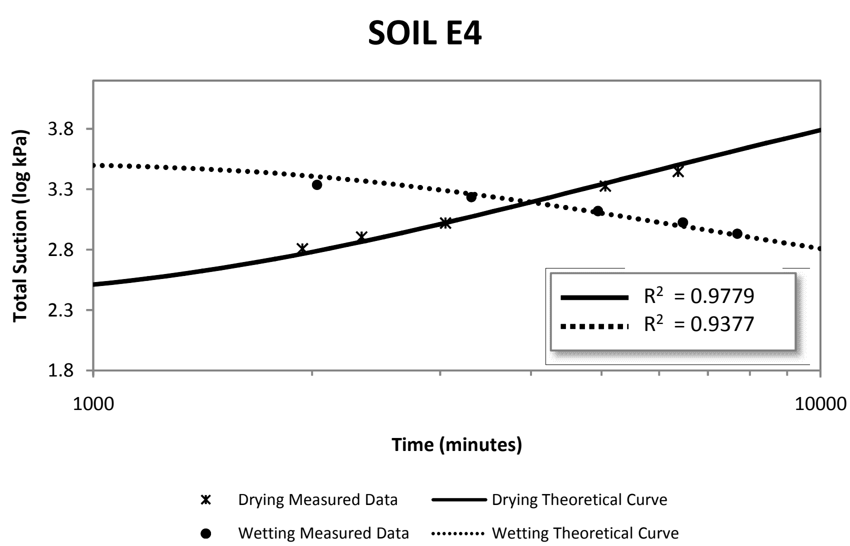


Specimen No.: **SOIL E4**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.30 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	3.35 log kPa		Initial Suction:	3.52 log kPa	
Psychrometer Location:	14.6 cm		Psychrometer Location:	14.6 cm	
Sample Length:	19.6 cm		Sample Length:	19.6 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	1940	2.810		2030	3.339
	2340	2.905		3310	3.237
	3050	3.021		4940	3.120
	5060	3.329		6470	3.028
	6370	3.448		7680	2.934

Drying Diffusion Coefficient: **$4.58x10^{-3}\ cm^2/min$**

Wetting Diffusion Coefficient: **$5.74x10^{-3}\ cm^2/min$**



Specimen No.: **SOIL E5**

Drying Test

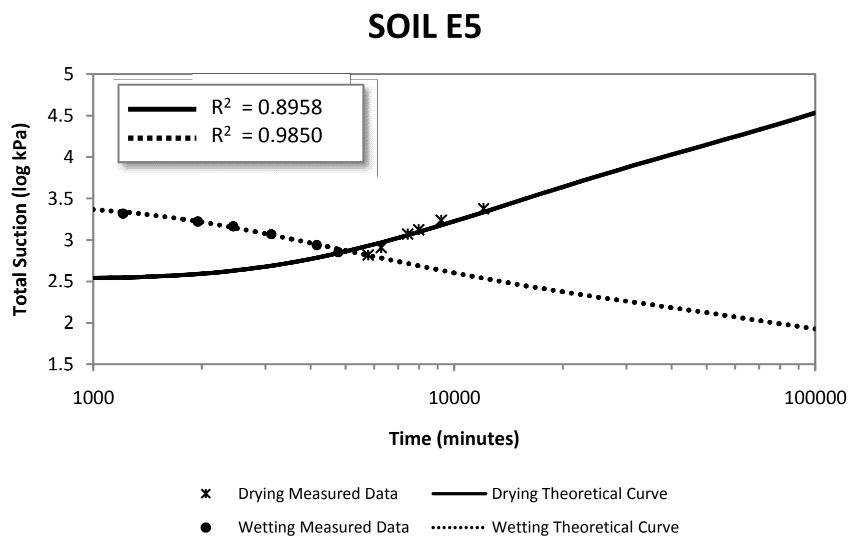
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	5.24 log kPa	
Initial Suction:	2.55 log kPa	
Psychrometer Location:	12.8 cm	
Sample Length:	16.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)
	5780	2.821
	6280	2.907
	7440	3.071
	7980	3.122
	9210	3.238
	12050	3.377

Drying Diffusion Coefficient: **1.18×10^{-3} cm^2/min**

Wetting Test

Soaking Suction:	1.75 log kPa	
Initial Suction:	3.42 log kPa	
Psychrometer Location:	12.8 cm	
Sample Length:	16.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)
	1210	3.320
	1950	3.222
	2440	3.164
	3110	3.073
	4160	2.938
	4770	2.854

Wetting Diffusion Coefficient: **1.63×10^{-3} cm^2/min**

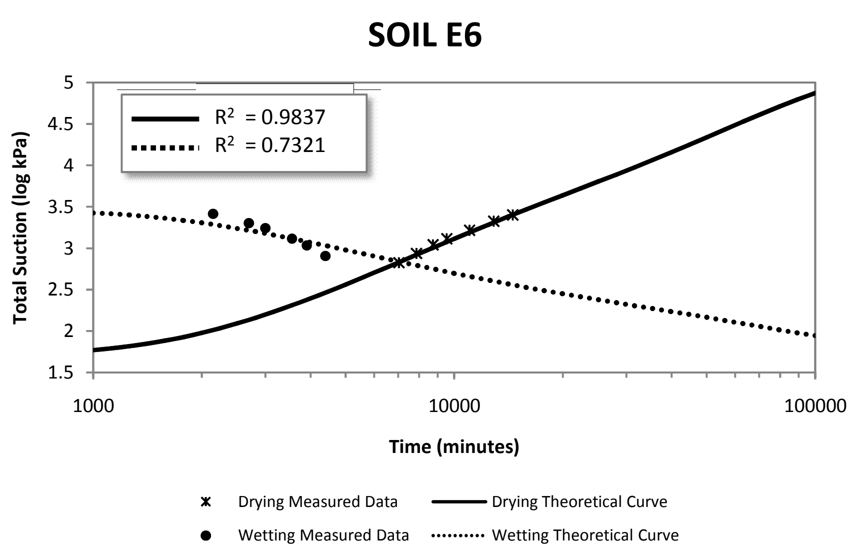


Specimen No.: **SOIL E6**

Drying Test			Wetting Test		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.25 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	1.73 log kPa		Initial Suction:	3.46 log kPa	
Psychrometer Location:	13.8 cm		Psychrometer Location:	13.8 cm	
Sample Length:	18.8 cm		Sample Length:	18.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	7030	2.828		2150	3.418
	7860	2.940		2700	3.305
	8730	3.040		3000	3.244
	9530	3.113		3550	3.118
	11020	3.217		3900	3.036
	12870	3.326		4400	2.908
	14540	3.402			

Drying Diffusion Coefficient: **3.10x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **4.10x10^{-3} cm^2/min**

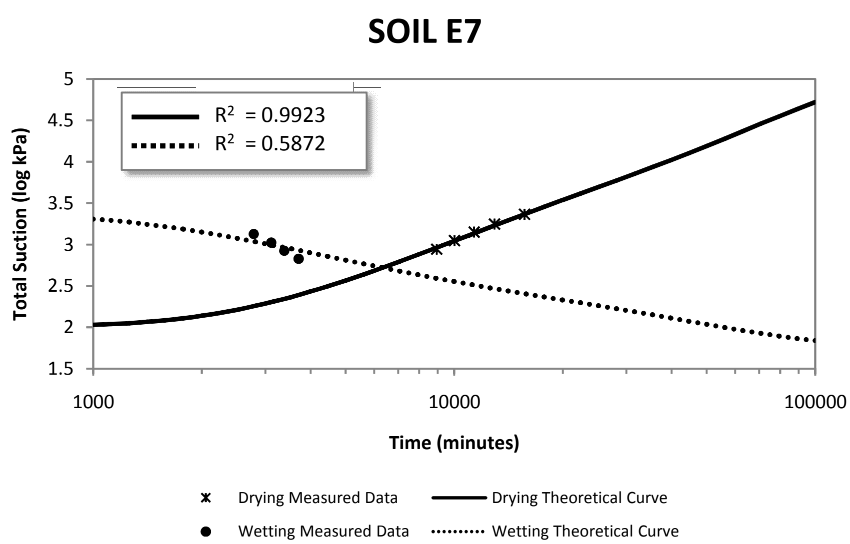


Specimen No.: **SOIL E7**

Drying Test			**Wetting Test**		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.20 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.02 log kPa		Initial Suction:	3.37 log kPa	
Psychrometer Location:	12.4 cm		Psychrometer Location:	12.4 cm	
Sample Length:	17.4 cm		Sample Length:	17.4 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	8950	2.946		2780	3.129
	10020	3.047		3110	3.022
	11340	3.149		3380	2.926
	12930	3.246		3710	2.830
	15660	3.365			

Drying Diffusion Coefficient: $\mathbf{2.26x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{2.74x10^{-3}\ cm^2/min}$

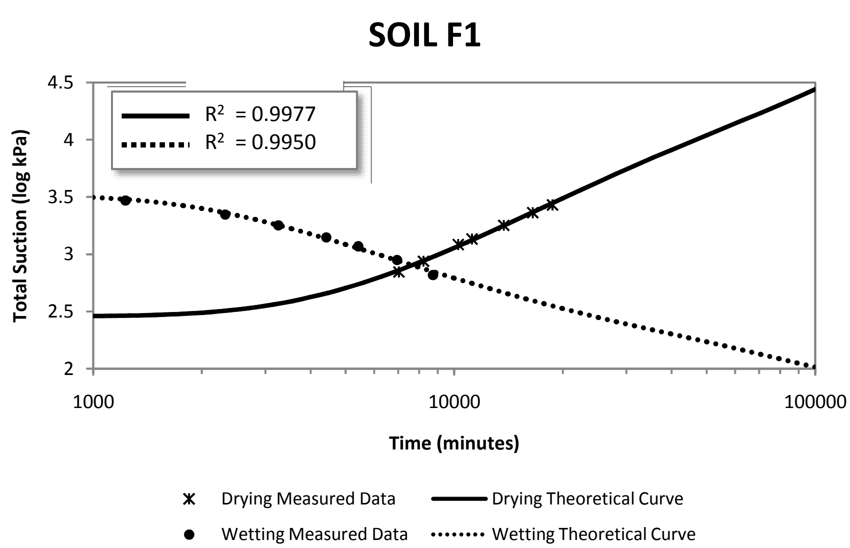


Specimen No.: **SOIL F1**

Drying Test			**Wetting Test**		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.27 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.48 log kPa		Initial Suction:	3.52 log kPa	
Psychrometer Location:	14.5 cm		Psychrometer Location:	14.5 cm	
Sample Length:	19.5 cm		Sample Length:	19.5 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	7030	2.847		1230	3.470
	8220	2.941		2320	3.348
	10260	3.084		3260	3.254
	11210	3.133		4420	3.148
	13720	3.254		5420	3.069
	16520	3.362		6940	2.952
	18740	3.431		8740	2.820

Drying Diffusion Coefficient: $\mathbf{1.37x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{1.82x10^{-3}\ cm^2/min}$

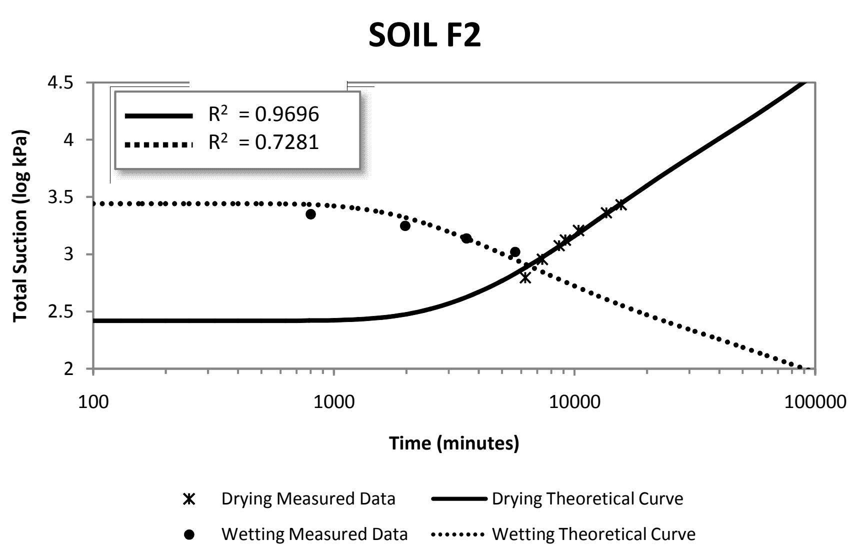


Specimen No.: **SOIL F2**

Drying Test			**Wetting Test**		
Evaporation Coefficient:	0.54 cm^{-1}				
Atmospheric Suction:	5.23 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.43 log kPa		Initial Suction:	3.45 log kPa	
Psychrometer Location:	13.8 cm		Psychrometer Location:	13.8 cm	
Sample Length:	18.8 cm		Sample Length:	18.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	6240	2.796		800	3.349
	7340	2.955		1980	3.250
	8620	3.077		3560	3.140
	9150	3.124		5660	3.021
	10400	3.207			
	13550	3.364			
	15620	3.434			

Drying Diffusion Coefficient: **1.74x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **1.95x10^{-3} cm^2/min**

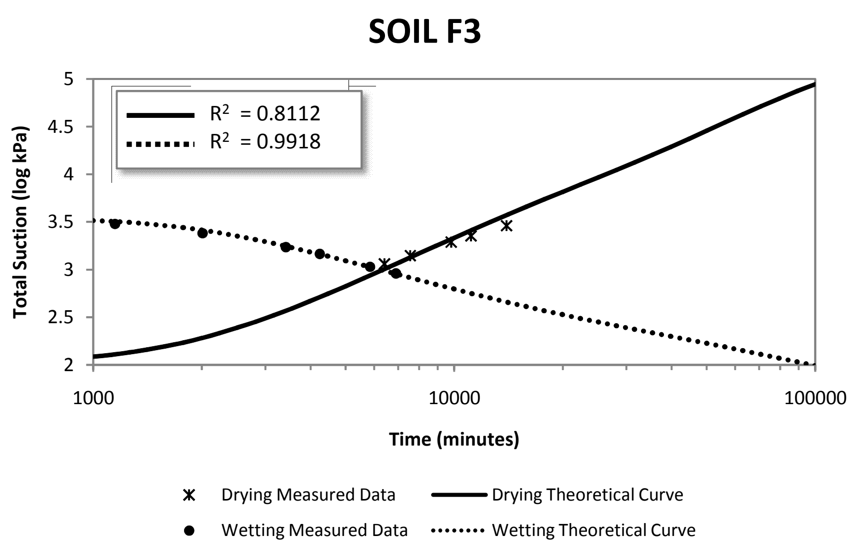


Specimen No.: **SOIL F3**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.28 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.05 log kPa		Initial Suction:	3.54 log kPa	
Psychrometer Location:	14.5 cm		Psychrometer Location:	14.5 cm	
Sample Length:	19.8 cm		Sample Length:	19.8 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	6410	3.060		1150	3.480
	7550	3.147		2010	3.383
	9820	3.288		3420	3.235
	11140	3.355		4240	3.164
	13970	3.463		5840	3.032
				6900	2.959

Drying Diffusion Coefficient: $\mathbf{3.47x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{2.08x10^{-3}\ cm^2/min}$



Specimen No.: **SOIL F4**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	5.28 log kPa
Initial Suction:	2.05 log kPa
Psychrometer Location:	14.5 cm
Sample Length:	19.8 cm
Suction Measurements:	

Time (min)	Suction (log kPa)
7470	2.862
8480	2.960
9540	3.028
11860	3.170
14180	3.278

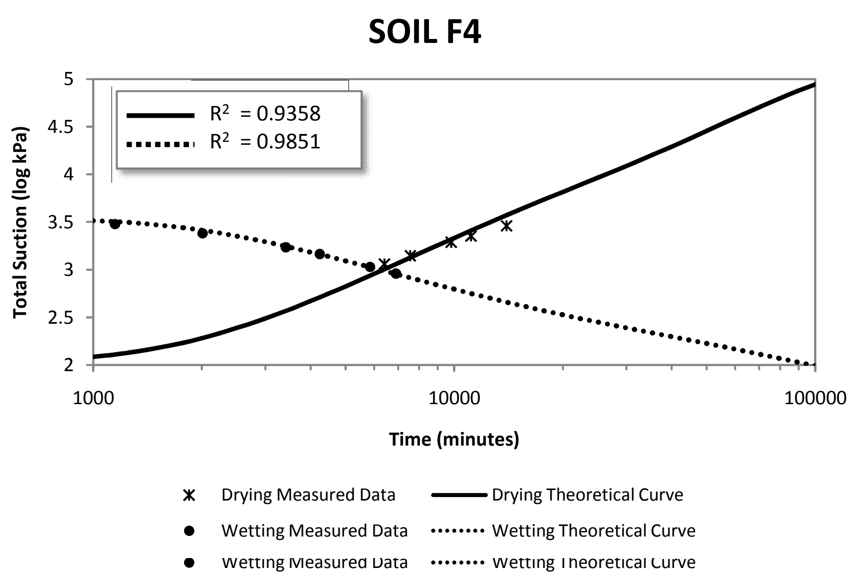
Drying Diffusion Coefficient: **3.47×10^{-3} cm^2/min**

Wetting Test

Soaking Suction:	1.75 log kPa
Initial Suction:	3.54 log kPa
Psychrometer Location:	14.5 cm
Sample Length:	19.8 cm
Suction Measurements:	

Time (min)	Suction (log kPa)
840	3.417
1350	3.309
1880	3.206
2410	3.114
2990	3.022
3660	2.925

Wetting Diffusion Coefficient: **2.08×10^{-3} cm^2/min**

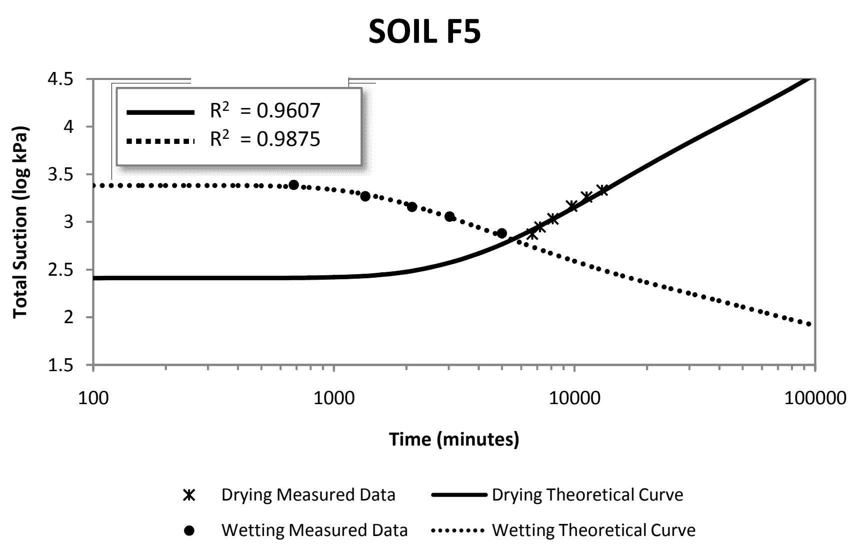


Specimen No.: **SOIL F5**

Drying Test			Wetting Test		
Evaporation Coefficient:	$0.54\ cm^{-1}$				
Atmospheric Suction:	5.25 log kPa		Soaking Suction:	1.75 log kPa	
Initial Suction:	2.42 log kPa		Initial Suction:	3.39 log kPa	
Psychrometer Location:	12.2 cm		Psychrometer Location:	12.2 cm	
Sample Length:	16.2 cm		Sample Length:	16.2 cm	
Suction Measurements:	Time (min)	Suction (log kPa)	Suction Measurements:	Time (min)	Suction (log kPa)
	6680	2.872		680	3.391
	7190	2.950		1350	3.269
	8120	3.032		2110	3.160
	9730	3.166		3020	3.056
	11220	3.265		4980	2.884
	13020	3.336			

Drying Diffusion Coefficient: $\mathbf{1.21x10^{-3}\ cm^2/min}$

Wetting Diffusion Coefficient: $\mathbf{1.63x10^{-3}\ cm^2/min}$

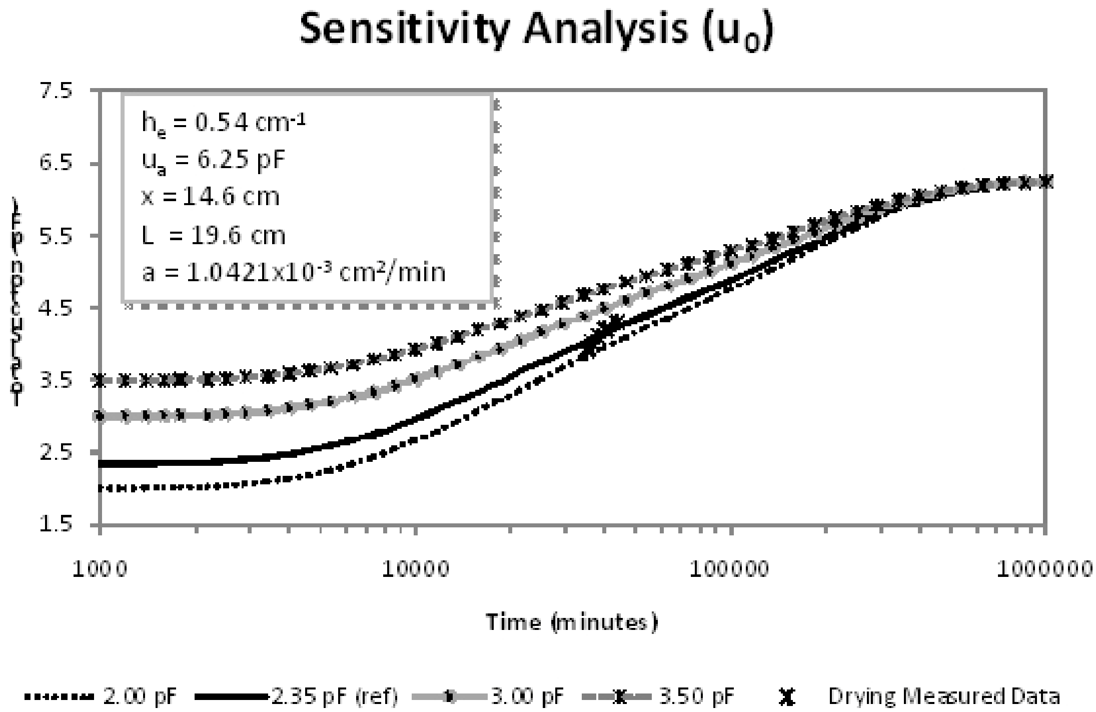


APPENDIX B

SENSITIVITY ANALYSIS ON INITIAL SUCTION

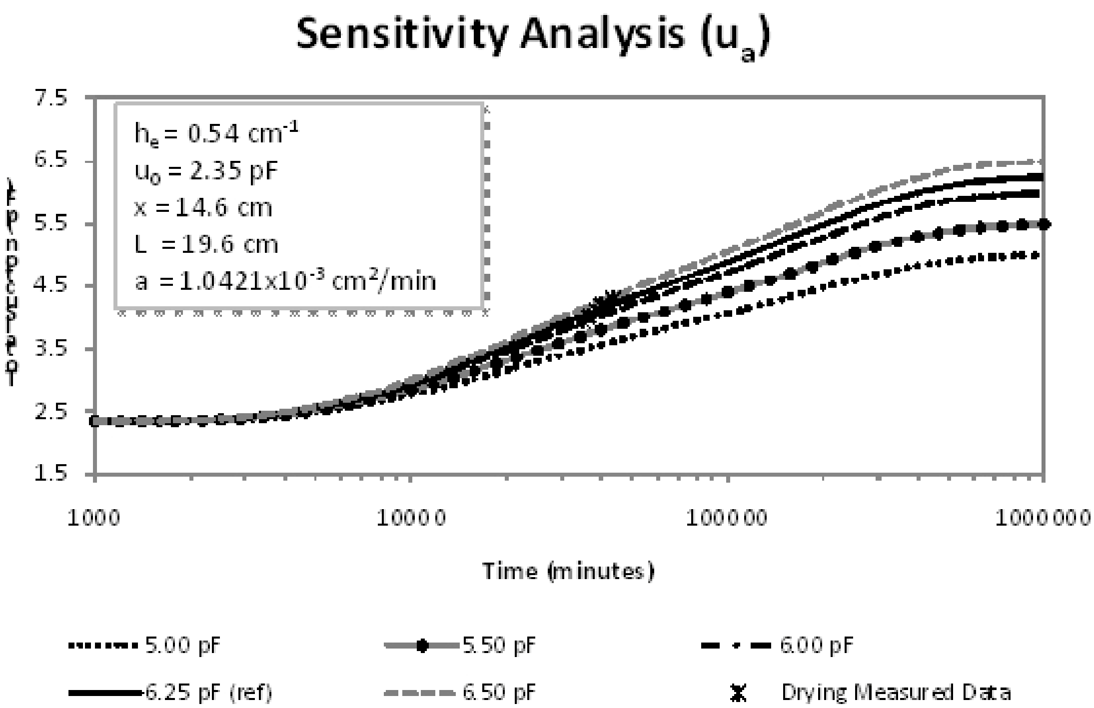
For the measured data set given below, the initial suction is varied while the evaporation coefficient, atmospheric suction, psychrometer distance, and sample length. The reference initial suction for this test is 2.35 pF.

MEASURED DATA	
Drying (min)	**Suction (pF)**
34810	3.943
36260	4.021
38130	4.104
40130	4.202
43470	4.306



SENSITIVITY ANALYSIS ON ATMOSHERIC SUCTION

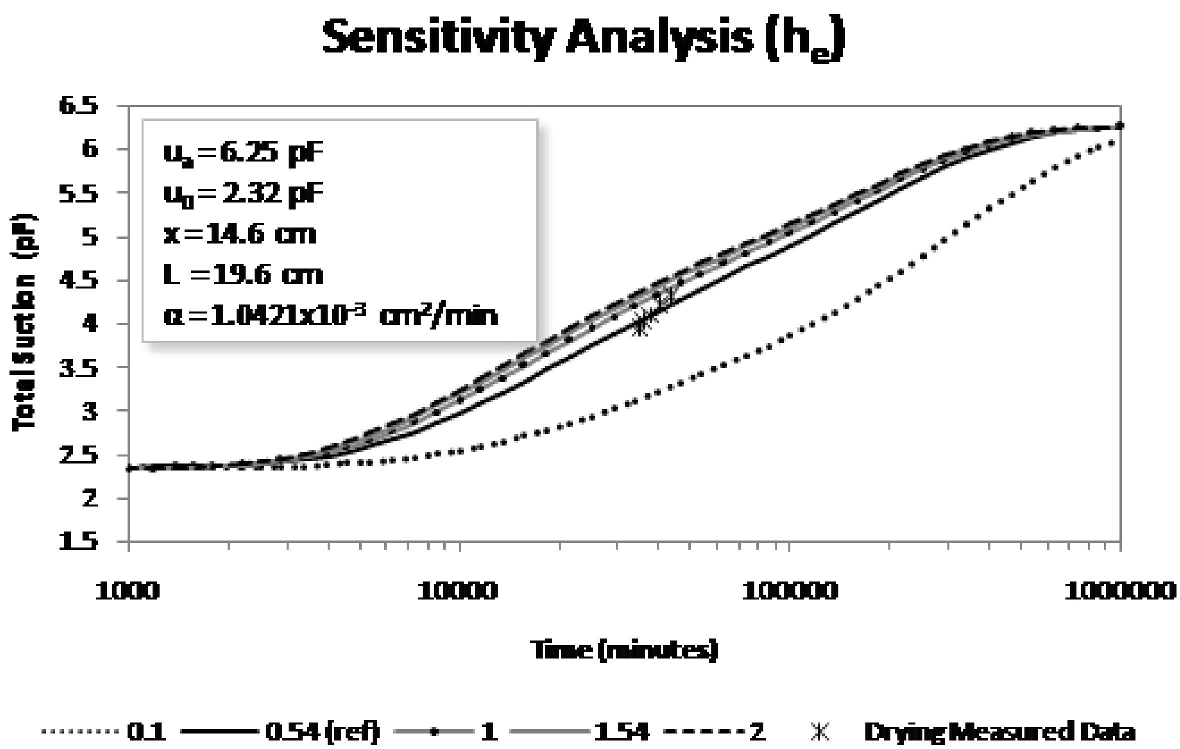
For the measured data set (page 74), the atmospheric suction is varied while the evaporation coefficient, initial suction, psychrometer distance, and sample length. The reference atmospheric suction for this test is 6.25 pF.



Sensitivity Analysis (u_a)
h_e = 0.54 cm^{-1}
u_o = 2.35 pF
x = 14.6 cm
L = 19.6 cm
a = 1.0421×10^{-3} cm^2/min
7.5
6.5
5.5
4.5
3.5
2.5
1.5
1000
10000
100000
1000000
Time (minutes)
5.00 pF
5.50 pF
6.00 pF
6.25 pF (ref)
6.50 pF
Drying Measured Data

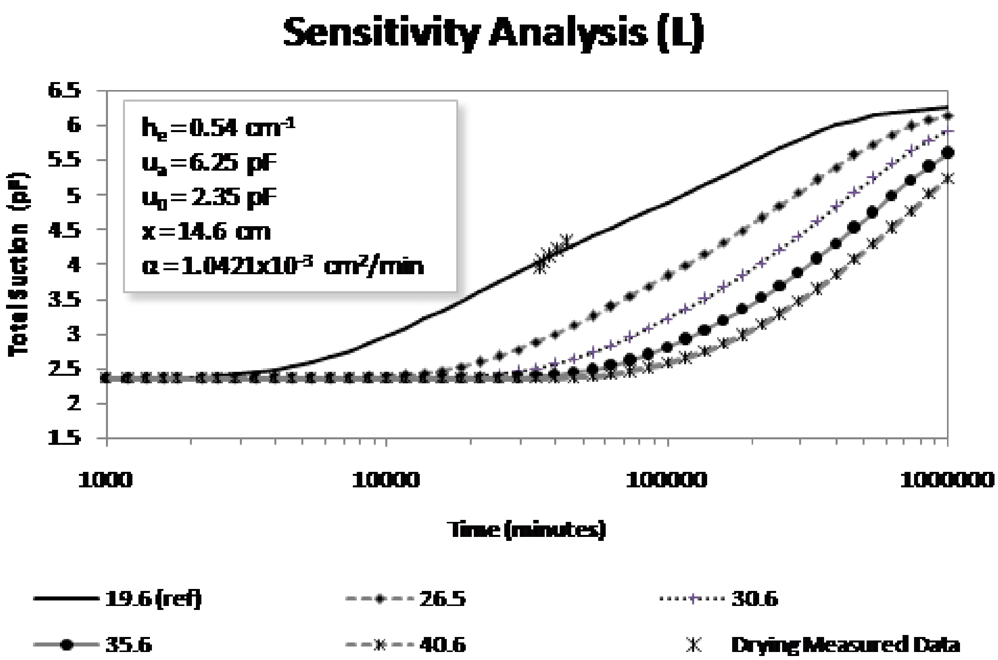
SENSITIVITY ANALYSIS ON EVAPORATION COEFFICIENT

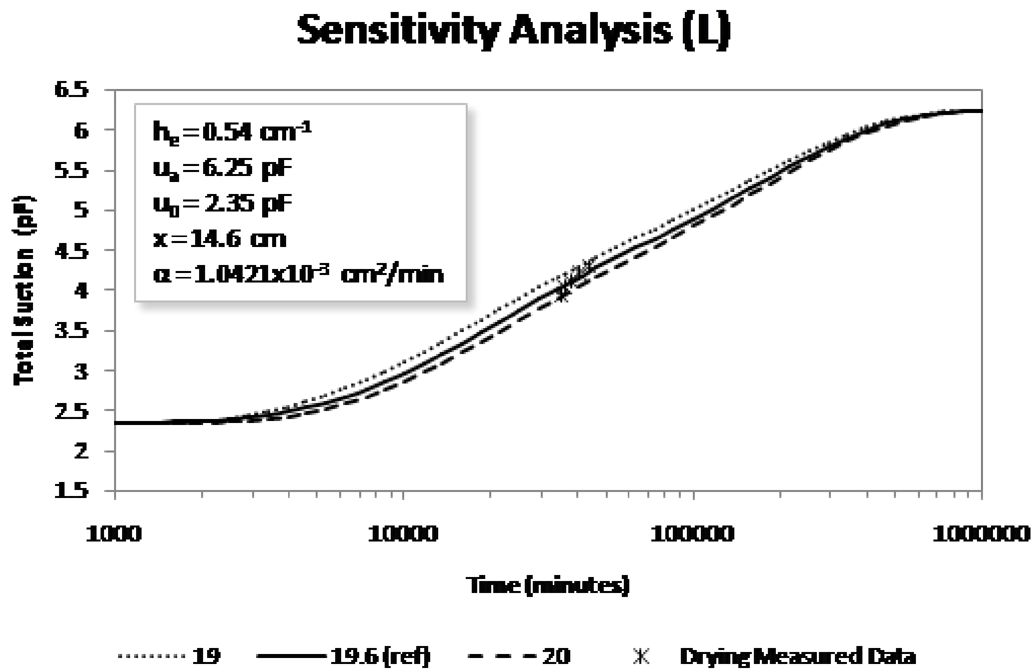
For the measured data set (page 74), the evaporation coefficient is varied while the atmospheric suction, initial suction, psychrometer distance, and sample length. The reference evaporation coefficient for this test is 0.54 cm^{-1}.



SENSITIVITY ANALYSIS ON SAMPLE LENGTH

For the measured data set (page 74), the sample length is varied while the evaporation coefficient, atmospheric suction, initial suction, and psychrometer distance. The reference sample length for this test is 19.6 cm.





Sensitivity Analysis (L)
$h_e = 0.54$ cm^{-1}
$u_a = 6.25$ pF
$u_0 = 2.35$ pF
x = 14.6 cm
$\alpha = 1.0421\times10^{-3}$ cm^2/min
Total Suction (pF)
Time (minutes)
19
19.6 (ref)
20
Drying Measured Data

SENSITIVITY ANALYSIS ON PSYCHROMETER DISTANCE

For the measured data set (page 74), the psychrometer distance is varied while the evaporation coefficient, atmospheric suction, initial suction, and sample length. The psychrometer distance for this test is 14.6 cm.